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NICKEL IN IGNEOUS ROCKS.[1]

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[1] For geologic field work in connection with this investigation I have received financial aid from the Foundation of the Technical University of Norway.

The results of my study are offered to ECONOMIC GEOLOGY in homage to the progress made by American investigators in applied geology during recent decades.

J. H. L. V.

[2] Revised and re-written by F. L. Ransome.

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NICKEL IN NORITES AND RELATED ROCKS OF NORWAY.

In order to contribute to our knowledge of the occurrence of nickel in gabbroitic, and particularly in noritic, rocks and to study the relation between the proportion of nickel in the rocks themselves and in the enclosed deposits of nickeliferous pyrrhotite, I collected in 1918 a number of representative samples of these rocks from Norwegian localities. Prof. V. M. Goldschmidt, of Christiania, kindly had the samples analyzed by Miss Siri Vogt, in his laboratory, where special experience had been gained in this kind of work.

The samples were dissolved in sulphuric and hydrofluoric acid and the nickel precipitated with dimethylglyoxime. The precipitate was dissolved in sulphuric acid and the nickel determined electrolytically. Each analysis was made in duplicate and the mean taken of the closely accordant results. The material ana-

lyzed was selected so as to contain as little pyrrhotite or pyrite as possible and in some samples these minerals were wholly absent. Pyrite is not attacked by sulphuric and hydrofluoric acid and the quantity of nickel derived from pyrrhotite probably does not exceed 0.002 per cent. in any determination, and in most is less than 0.001 per cent. All the samples from norite masses known to contain deposits of nickeliferous pyrrhotite were collected by myself at some distance from the ore bodies.

The results of these determinations are as follows. the nickel being given as the metal, Ni:

TABLE I.

NICKEL DETERMINATIONS OF NORWEGIAN ROCKS.

No.	Locality.	Name.	Percentage of Ni.
1.	Erteli, Ringerike	Norite	0.023
2.	" "	Olivine norite	0.093
3.	" "	Amphibole peridotite	0.124
4.	Skougen, Bamle	Norite	0.030
5.	" "	Segregation of ferro-magnesian silicates, rich in hypersthene	0.089
6.	Hosanger	Hypersthenite-norite[1]	0.058
7.	"	Segregation of ferromagnesian silicates, rich in hypersthene	0.126
8.	Romsaas	Hypersthene orb from orbicular quartz norite	0.049
9.	Mølland, Iveland	Hypersthenite-norite	0.070
10.	Høiaas, Tvedestrand	Olivine gabbro	0.067

Some of the rocks from the localities given in Table I. were subjected to complete chemical analysis and the results, with analyses of norites from some other Norwegian localities, are given in Table II. In these analyses the nickel is recorded as oxide, NiO.

Analyses 1, 4, 6, and 11 were made by Mr. O. Røer for my treatise "Die Sulfid-Silikat-Schmelzlösungen."[2] The nickel determinations for 1, 4, and 6 were made on the same general rock samples as the analyses but on pieces selected as being as free

[1] By hypersthenite-norite is meant a variety of norite with only from 20 to 40 per cent. of calcic plagioclase.

[2] *Norsk. Geol. Tideskrift*, IV., p. 43, 1917.

TABLE II.

ANALYSES OF NORWEGIAN NORITES.

	1	4	6	8a	8b	11	12	13	14	15
SiO_2	46.30	51.48	49.10	53.3	53.7	51.90	52.30	50.10	50.70	55.90
TiO_2	.48	1.09	1.09	.....	.82	.72	.62	.5	.25	.45
Al_2O_3	20.20	14.40	8.19	3.0	9.9	18.00	10.28	18.5	20.70	17.50
Cr_2O_3	.....	.....	.16	.....	.....	.....	.....	.09	.08	.....
Fe_2O_3	1.52	1.44	2.41	1.2	.4	1.12	.37	.5	.50	.08
FeO	7.74	9.42	9.00	16.5	11.2	6.95	8.80	6.3	4.38	6.97
MnO	.17	.17	.16	.3	.4	.11	.20	.1	.07	.09
MgO	9.07	10.89	13.87	23.7	15.8	7.61	18.30	12.54	9.43	5.98
BaO	.....	.....	.07	.....	.....	.....	tr.	.....	tr.	tr.
CaO	9.93	7.17	12.02	2.0	4.1	8.63	6.06	8.65	10.35	8.32
Na_2O	1.48	2.15	1.38	.....	1.7	2.86	1.14	1.5	1.58	2.75
K_2O	.66	.58	.72	.....	.7	.84	.58	.6	.69	1.50
$H_2O-110°$	.31	.14	.05	.....	} 1.0	.11	.06	} .7	.07	.07
$H_2O+110°$	1.75	.56	.72	.....		.67	.86		1.12	.50
CO_2	.53	.53	.91	.....		.22	.61		.40	.20
P_2O_5	.04	.03	.20	.....	.32	.38	.05	.05	tr.	.05
S	.07	.24	.41	.....	.....	.08	.09	.05	.05	.05
	100.25	100.29	100.46	100.0	100.0	100.20	100.32	100.2	100.37	100.41
Less $\frac{1}{2}S=O$	.03	.12	.20			.04	.05		.03	.03
	100.22	100.17	100.26	100.0	100.0	100.16	100.27	100.2[2]	100.34	100.38
NiO	.028	.038	.074	.062	(.042)	.....	.....	.....	.....	.....

1. Norite, Erteli, Ringerike.
4. Norite, Skougen, Bamle.
6. Hypersthenite-norite, Hosanger.
8a. Hypersthene from orbicular quartz-norite, Romsaas. Mean of 4 analyses.
8b. Orbicular quartz-norite, Romsaas. Mean of 2 analyses.
11. Norite, Høiaas, Tvedestrand.
12. Norite, Raana, Ofoten.
13. Norite, Raana, Ofoten.
14. Norite, Raana, Ofoten.
15. Quartz-norite, Raana, Ofoten.

as possible from sulphides. Analysis 8a is of hypersthene separated from the orbs of the orbicular quartz norite at Romsaas. It is a mean of 4 analyses previously made and the composition of the quartz norite (8b) is a mean of 2 (partly of 3) previously published analyses.[4] The determination of nickel in number

[2] Contains also .09 per cent. of V_2O_3.

[4] Vogt, J. H. L., "The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks," *Jour. of Geol.*, vol. 29, p. 430, 1921.

8a was made on a hypersthene orb, with no trace of pyrrhotite, from the same locality. Analyses 12 to 15 are taken from a paper by S. Foslie[5] on the norite at Raana, in Ofoten.

For the remaining rocks listed in Table I., of which chemical analyses have not been made, I have calculated the approximate chemical composition from the mineralogical composition, aided by available chemical analyses of mineralogically very similar rocks. The results, which appear in Table III., are of course not exact, especially for numbers 3 and 5, but the errors are too small to be important in the use here made of the calculated compositions.

TABLE III.

APPROXIMATE CHEMICAL COMPOSITION OF CERTAIN NORWEGIAN NICKEL-BEARING ROCKS AS CALCULATED FROM THEIR MINERAL COMPONENTS.

	2	3	5	7	9	10
SiO_2	44	43	47	49	52	45
TiO_2	.5	.3	1	1	.3	.3
Al_2O_3	12	3.5	6	5	10	13
Fe_2O_3	1	2.5	4.5	2	1.7	1
FeO	10	13	10	11	7	10
MgO	24	33	22	20	16	19
CaO	7	3.5	7	11	11	10
Na_2O	1.2	.6	1	.5	1.7	1.2
K_2O	.3	.6	1	.5	.3	.5
P_2O_5	.....	.....	.5	.....	.....	.....
	100	100	100	100	100	100
NiO	.118	.158	.113	.160	.089	.085

2. Olivine norite. Erteli, Ringerike.
3. Amphibole peridotite. Erteli, Ringerike.
5. Segregation of ferromagnesian silicates, rich in hypersthene. Bamle.
7. Segregation of ferromagnesian silicates, rich in hypersthene. Hosanger.
9. Hypersthenite-norite. Mølland, Iveland.
10. Olivine gabbro. Høiaas, Tvedestrand.

The norite from Erteli, with hyperitic or ophitic structure, is calculated from chemical analysis No. 1, of Table II., and from examination in thin section, to have approximately the following mineralogical composition:

[5] *Norges Geologiske Undersøkelses Aarbok*, 1920.

	Per Cent.
Hypersthene	44
Labradorite	55
Magnetite and ilmenite	1
Pyrrhotite and pyrite	.18
Apatite	.09

The hypersthene, partly changed to amphibole, contains from 32 to 36 per cent. of $FeSiO_3$. The labradorite is calculated as $An_{69}Ab_{25}Or_6$. Biotite is absent.

The chemical composition of the olivine norite from Erteli, number 2 of Table III., is computed from the following estimated mineral composition:

	Per Cent.
Olivine	45
Hypersthene	10
Brown amphibole	10
Labradorite	35

The olivine, as shown by measurement of its optical axial angle, contains about 20 per cent. of Fe_2SiO_4. Much of it shows strong reaction rims and some is completely transformed. The brown amphibole is primary and both it and the hypersthene are only moderately rich in iron. The labradorite is about An_3Ab_1, with a small admixture of orthoclase molecule.

The amphibole peridotite, number 3 in Table III., a rock of small areal extent, is so altered that the original composition in primary minerals can not be closely calculated. From microscopical examination I have estimated the original mineralogical composition as follows:

	Per Cent.
Olivine	55
Light brown amphibole	25
Bronzite-hypersthene	15
Biotite	5

The olivine, as shown by its axial angle, contains about 17 per cent. of Fe_2SiO_4.

The norite from Skougen, Bamle, is calculated from its chemical analysis (No. 4) and a microscopical examination to consist of:

	Per Cent.
Hypersthene	45
Biotite	4
Labradorite	49
Ilmenite and magnetite	1
Pyrite and pyrrhotite	.5
Apatite	.07

The hypersthene has about 30 per cent. $FeSiO_3$ and the labradorite is calculated as $An_{58}Ab_{38.5}Or_{3.5}$. The hypersthene is only slightly changed to amphibole.

The segregation of ferromagnesian silicates from Meinkjaer, Bamle, for which a nickel determination (No. 5) is given in Table I., consists of about 40 per cent. of hypersthene, containing about 20 per cent. of $FeSiO_3$, 40 per cent. of primary brown hornblende, 5 per cent. of augite, 14 per cent. of biotite and a little over 1 per cent. of apatite. Plagioclase is absent. In two samples of similar material from Nedre Vissestad, Bamle, a little olivine, with about 20 per cent. of Fe_2SiO_4, was noted.

The hypersthenite-norite from Litland, Hosanger (analysis No. 6 in Table II.), has the following calculated composition:

	Per Cent.
Hypersthene	60
Primary brown-green hornblende	12
Biotite	5
Labradorite	20
A little apatite and pyrrhotite.	

The hypersthene, which includes some diallage, has about 27 per cent. of $FeSiO_3$. The labradorite is a rather calcic variety.

The plagioclase-free segregation (No. 7 of Table I.), from Bysheim, 1 kilometer from the main hypersthenite-norite locality of Hosanger, consists of hypersthene with about 22 per cent. $FeSiO_3$, some diallage, amphibole and a little biotite but no sulphides. This rock, as well as the analogous rock from Bamle (No. 5), is closely related to the bahiaite described by H. S. Washington.

The quartz norite from Romsaas[6] (No. 8b of Table II.) has approximately the following mineralogical composition:

[6] Vogt, J. H. L., *op. cit.*, pp. 430–435 and a previous treatise of C. Bugge.

	Per Cent.
Hypersthene	63
Biotite	8
Labradorite	24
Quartz	4

A little apatite and rutile.

The hypersthene is calculated to contain 28 per cent. of $FeSiO_3$ and 0.049 per cent. of nickel. The biotite is calculated to contain .03 nickel. The estimate for the rock as a whole is .033 per cent. of nickel, or .042 per cent. of NiO. This latter figure is inserted in parentheses in Table II.

The hypersthenite-norite from Mølland, Iveland (No. 9 in Table I.), consists of about 30 per cent. of labradorite (Ab_2An_3), 35 per cent. of hypersthene (20 per cent. $FeSiO_3$), 30 per cent. of diopsidic augite and 5 per cent. of amphibole.

The olivine gabbro from Høiaas near Tvedestrand (No. 10 of Table I.) consists of about 35 per cent. of olivine (with 23 per cent. Fe_2SiO_4), 15 per cent. of diallage, 10 per cent. of primary brown amphibole, 5 per cent. of biotite and 35 per cent. of labradorite (Ab_1An_3).

It may be seen from the foregoing that various rocks from a number of small eruptive fields all show a definite relation between mineral composition and nickel content. At Erteli, for example, in the series norite, olivine norite and amphibole peridotite, the corresponding nickel contents, expressed as NiO, are .028, .118 and .158 per cent. At Bamle the norite shows .038 per cent. of NiO and the hypersthenic segregations .113 per cent. At Hosanger the norite contains .074, and the hypersthenic segregations .160, per cent. of NiO. The general results may be tabulated as follows: (p. 315.)

Thus, in the main, with increase in the quantity of hypersthene there is an increase in the contents of nickel. Similarly, in the olivinitic rocks, the nickel, as is to be expected, varies directly with the amount of olivine present.

As will be shown in the second part of this paper, the nickel in the rocks here studied occurs in the ferromagnesian silicates, chiefly in the hypersthene and olivine, although to some extent

TABLE IV.

RELATION OF MINERAL COMPOSITION AND NICKEL CONTENT OF NORWEGIAN ROCKS.

Name.	Locality.	Mineral Composition (Per Cent.).	NiO (Per Cent.).
Norite	Erteli	Labradorite 55, hypersthene (with 32 per cent. $FeSiO_3$) 44.	.028
Norite	Bamle	Labradorite 49, hypersthene (with 31 per cent. $FeSiO_3$) 45, biotite 4.	.038
Quartz-norite	Romsaas	Labradorite 24, quartz 4, hypersthene (with 28 per cent. $FeSiO_3$) 63, biotite 8.	.042
Hypersthenite-norite	Hosanger	Labradorite 20, hypersthene (with 27 per cent. $FeSiO_3$ and some diallage) 60, amphibole 12, biotite 5.	.074
Hypersthenite-norite	Iveland	Labradorite 30, hypersthene (with 20 per cent. $FeSiO_3$) 35, augite 30, biotite 5.	.089
Hypersthenic segregation	Bamle	Hypersthene (with 20 per cent. $FeSiO_3$) 40, amphibole 40, augite 5, biotite 14.	.113
Hypersthenic segregation	Hosanger	Hypersthene (with 22 per cent. $FeSiO_3$ and some diallage) 80, amphibole and biotite 20.	.160
Olivine gabbro	Høiaas	Olivine (with 23 per cent. Fe_2SiO_4) 35, diallage 15, amphibole 10, biotite 5, labradorite 35.	.085
Olivine norite	Erteli	Olivine (with 20 per cent. Fe_2SiO_4) 45, hypersthene 10, amphibole 10, labradorite 35.	.118
Amphibole peridotite	Erteli	Olivine (with 17 per cent. Fe_2SiO_4) 55, amphibole 25, hypersthene 15, biotite 5.	.158

in the augite, amphibole and biotite. This fact, if we know the nickel content of the whole rock, enables us to calculate approximately the nickel content of the constituent silicates. Thus the norite from Erteli carries .028 per cent. of NiO and 44 per cent. of hypersthene, with no biotite. The hypersthene therefore contains about .063 per cent. of NiO. The norite from Bamle contains .038 of NiO and 45 per cent. of hypersthene, with 4 per cent. of biotite. The biotite is assumed to contain half as much nickel as the hypersthene. Any possible small error in this assumption is negligible, as the amount of biotite is so much less than that of hypersthene. The hypersthene is accordingly cal-

culated to contain .081 per cent. of NiO_4. For the Romsaas orbicular quartz diorite we have an analysis of the hypersthene itself, with .062 per cent. of NiO_2. The mixture of hypersthene, diallage or amphibole, and biotite in the hypersthenite-norite of Hosanger is calculated to contain .092 per cent. of NiO. The hypersthene, augite and amphibole of the hypersthenite-norite from Iveland contain .100 per cent. of NiO. In the hypersthene-rich segregations from Bamle the ferromagnesian constituents are calculated to contain .113 per cent. of NiO and the similar constituents of the Hosanger segregations, .160 per cent. of NiO.

The ratios of NiO to MgO in the various rocks described, expressed in percentages, are as follows:

	NiO ÷ 100 MgO
Hypersthene orb, Romsaas	.26
Norite, Erteli	.31
Norite, Bamle	.35
Hypersthenite-norite, Hosanger	.53
Hypersthenite-norite, Iveland	.55
Segregations, Bamle	.51
Segregations, Hosanger	.80
Olivine norite, Erteli	.49
Olivine gabbro, Høiaas	.44
Amphibole peridotite, Erteli	.48

The significance of these figures will be discussed in the second part of this paper.

GENERAL OCCURRENCE OF NICKEL IN IGNEOUS ROCKS.

REVIEW OF PREVIOUS DETERMINATIONS.

Sources.

I shall first review the previous determination of nickel in rock-forming silicate minerals and in igneous rocks as a whole, using for this purpose the modern analyses collected in Doelter's "Handbuch der Mineralchemie," H. S. Washington's "Chemical Analyses of Igneous Rocks, 1884–1913,"[7] and F. W. Clarke's "Analyses of Rocks and Minerals from the Laboratory of the United States Geological Survey, 1880–1908."[8] There are considered also some analyses from various other recent publications.

[7] U. S. Geol. Survey, Profess. Paper 99, 1917.

[8] U. S. Geol. Survey, Bull 419, 1910.

Many of the older determinations of nickel in minerals and rocks are too inexact to serve as the basis for theoretical conclusions and even many modern analyses where the quantity of nickel is small and the result given in only two decimal places are of little value in the present study.

In Rock-Making Minerals.

Olivine.—Thirteen analyses of iron-poor olivine from dunites, saxonites, and olivinitic basaltic bombs show from 0.19 to 0.50 per cent. of NiO, with in two instances some cobalt. The average is 0.33 per cent., inclusive of any cobalt present. These olivines contain from 47 to 51 per cent. of MgO and from 7 to 14 per cent. of Fe_2SiO_4. For 12 of the analyses the proportions of NiO to 100 parts by weight of MgO are 1.01, 0.97, 0.89, 0.82, 0.74, 0.71, 0.67, 0.65, 0.57, 0.51, 0.46 and 0.40. In the remaining analysis MgO was not determined.

Four analyses of iron-rich olivines (with 18–30 per cent. Fe_2SiO_4) from olivine gabbro and basalt show from 0.15 to 0.32 per cent. of NiO, or an average of 0.21 per cent. The percentage ratio of NiO to MgO is 1.06, 0.75, 0.43 and 0.36.

It appears that the iron-poor olivines as a whole contain more nickel than the iron-rich olivines.

Orthorhombic Pyroxene.—Enstatite or bronzite, with about 8 per cent. of $FeSiO_3$, from the "enstatite-serpentine rock" of Granville, Mass. (Clarke, *op cit.*, p. 19), gives 34.40 per cent. of MgO and 0.23 per cent. of NiO, or a percentage ratio of 0.67 NiO. The associated serpentine, derived from the enstatite, contains 0.45 per cent. NiO and 0.05 CoO.

The available data for Norwegian hypersthenes have already been presented. These analyses show an increasing content in NiO with increase in MgO.

Monoclinic Pyroxene.—A lime-poor augite from diabase of the Åland Islands[9] gives 16.65 per cent. of MgO with 0.05 per cent. of NiO or a percentage ratio of about 0.3 NiO. Augite from the quartz diabase of Onega Lake, Finland,[10] contains 11.37

[9] Wahl, W., Tscherm. Min. Petrogr. Mitth., 26, 1906.

[10] Wahl, *loc. cit.*

per cent. MgO and 0.04 NiO, or a percentage ratio of 0.35 NiO. Augite from a nepheline basalt from Texas[11] contains 12.25 per cent. MgO and 0.05 per cent. NiO, or a percentage ratio of 0.4 NiO. Augite from a syenitic lamprophyre from Colorado[12] contains 14.21 per cent. MgO and 0.03 per cent. NiO, a ratio of 0.2 NiO. Augite from analcite basalt, Sardinia,[13] contains 13.73 per cent. MgO and 0.02 per cent. NiO, or a percentage ratio of 0.15 NiO. Augite from Hannebacher Kessel[14] contains 12.15 per cent. of MgO and 0.04 per cent. of NiO, or a percentage ratio of 0.4 NiO.

Amphibole.—Amphibole separated from quartz monzonite from the Sierra Nevada, Cal.,[15] contains 13.06 per cent. of MgO and 0.02 per cent. of NiO + CoO. This corresponds to 100 parts of MgO to about 0.15 part of NiO + CoO.

Kærsutite (linosite) from lapilli from the crater of Mte. Rosso, Island of Linosa, Italy,[16] contains 12.47 per cent. of MgO and 0.10 per cent. of NiO—an unusually high percentage.

Mica.—Bronze mica (biotite) from the Laurel Creek corundum mine, Georgia,[17] contains 0.34 per cent. of NiO. Lepidomelane from Port Henry, New York, contains 0.30 per cent of NiO + CoO.[18]

Rubellane ("philadelphite"), from near Philadelphia,[19] contains 0.06 per cent. of NiO + CoO, with 0.08 per cent. of CuO.

These are rather exceptional biotites. The more ordinary sorts that occur in the common igneous rocks contain generally less NiO. For example, the biotite from the quartz monzonite from the Sierra Nevada (see under *amphibole*, above) contains 12.37

[11] Clarke, *op. cit.*, p. 262.

[12] Clarke, *loc. cit.*

[13] Washington, H. S., *Jour.Geol.*, vol. 22, p. 747, 1914, and *Amer. Jour. Sci.*, 4 ser., vol. 45, p. 468, 1918.

[14] "Uhlig. Abst. Neues Jahrb. f. Min., Geol., und Pal.," vol. 1, p. 25, 1912. (Doelter, *op. cit.*, vol. 2, p. 544.)

[15] Clarke, *op. cit.*, p. 158.

[16] Clarke, *op. cit.*, p. 158.

[17] Clarke, *op. cit.*, p. 289.

[18] Clarke, *op. cit.*, p. 291.

[19]

per cent. of MgO and 0.02 per cent. of NiO + CoO. This is 0.15 part of NiO to 100 parts of MgO. Stelzner[20] by very careful and detailed work found that the biotite from the Freiberg gneiss contains 8.70 per cent. of MgO and 0.028 per cent. of Ni + Co and the biotite from the Sulsbächle granite, in the Erzgebirge, 10.1 per cent. of MgO and 0.007 per cent. of Ni + Co.

In Rocks.

Peridotites.—Eleven analyses of dunites, saxonites, etc., with from 75 to 90 per cent. of olivine (7 to 15 per cent. of Fe_2SiO_4), show from 0.10 to 0.51 per cent. of NiO. Most have from 0.15 to 0.30 per cent. and the average is 0.20 per cent. of NiO. For every 100 parts of MgO these rocks show respectively 1.15, 0.95, 0.69, 0.58, 0.48, 0.35, 0.35, 0.34, 0.34, 0.23 and 0.22 NiO.

Two analyses by S. Foslie[21] of lherzolite and troctolite from Raana show 0.14 and 0.36 per cent. of Ni with respectively 0.12 and 0.28 per cent. of S. These rocks occur near sulphide deposits which carry about 7 per cent. nickel to 37 per cent. sulphur. Correction for admixed sulphides on this basis, gives about 0.117 and 0.307 per cent. of nickel or 0.15 and 0.37 per cent. of NiO in the silicate minerals.

Sixteen analyses of amphibole peridotite, augite peridotite, wehrlite, etc., give from 0.02 to 0.30 per cent. of NiO and an average of 0.12 per cent. For 100 parts of MgO, 11 of these analyses show respectively 0.90, 0.89, 0.79, 0.68, 0.48, 0.44, 0.35, 0.35, 0.35, 0.3, and 0.25 part of NiO. Five less satisfactory analyses give 0.25, 0.25, 0.15, 0.15, and 0.10 part of NiO to 100 MgO. In these amphibole peridotites the greater part of the nickel is in the olivine but some is present in the other ferromagnesian silicates. Olivines rich in Mg_2SiO_4 appear to carry more nickel than the less magnesic kinds.

From Clarke and Doelter are taken the following data relating to analyses of serpentine derived from olivinitic rocks.

3 analyses show 0.06–0.09 per cent. of NiO.

6 analyses show 0.10–0.19 per cent. of NiO.

[20] Stelzner, A. W., *Zeits. f. prakt. Geol.*, 1896.

[21] *Loc. cit.*

6 analyses show 0.21–0.29 per cent. of NiO.
1 analysis shows 0.33 per cent. NiO + CoO.
2 analyses show 0.40 and 0.47 per cent. of NiO.
2 analyses show 0.51 and 0.53 per cent. of NiO.
The average of the 20 analyses is 0.24 per cent. of NiO.

In addition there are some analyses of serpentine-like minerals formed under special conditions. Thus picrolite from Buck Creek, North Carolina, contains 0.61 per cent. of NiO and from Wilmington, Delaware, 0.71 per cent. According to Lindner[22] "williamsite" from Easton, Pennsylvania, contains 0.91 per cent. of NiO and "bowenite" from Smithfield, Rhode Island, 1.72 per cent., from Schwarzwald on Saale 2.14 per cent., and from Portjoy, Scotland, 2.83 per cent.

In this connection it may be remembered that talc, formed in the general process of serpentinization, may contain nickel. Various analyses show from 0.20 to 0.50 per cent. of NiO. Thus in serpentinization some nickel has been dissolved and redeposited. The normal process of serpentinization is represented by the equation:

$$2Mg_2SiO_4 + CO_2 + 2H_2O = H_4Mg_3Si_2O_9 + MgCO_3.$$

Thus pure Mg_2SiO_4 loses 1 part of MgO and gains 2 parts of H_2O. The net loss in weight is only 1.4 per cent. It must be remembered, however, that some Fe_2SiO_4 from the olivine is often carried away and considerable CaO and SiO_2 is lost from the silicate minerals that accompany the olivine. Peridotites may thus lose as much as 10 per cent. in weight by serpentinization. If the nickel originally present is retained, serpentine may contain one tenth more nickel than the original rock. Serpentine derived from dunite and other highly olivinitic rocks is thus likely to be especially rich in nickel. Here may be recalled the famous garnierite deposits in peridotite and serpentine. Moreover, by the normal lateritic decomposition of serpentine the residual material may be enriched in nickel, as well as in oxides of

[22] Lindner, A., "Ivang. Diss.," Breslau, 1893. Abst. in *Zeits. f. Krys. u. Min.*, vol. 25, p. 589, 1896.

iron and aluminum, as illustrated by the well-known lateritic iron-ore deposits of Cuba.

Hypersthene-amphibole Rocks (Bahiaite, etc.).—Pyroxenite, consisting of hypersthene and amphibole, from the divide between Meadow and Granite Creeks, Montana,[23] contains 24.10 per cent. of MgO and 0.11 per cent. of NiO, or a percentage ratio of 0.45 NiO.

Hypersthene-rich segregations in the norites of Bamle and Hosanger, Norway, contain 0.113 and 0.160 per cent. of NiO, or percentage ratios of 0.50 and 0.80 NiO, respectively, to 100 MgO.

Websterites.—These rocks are essentially diopside and bronzite, both poor in iron. The type rock from Webster, North Carolina, with much bronzite and little diopside, contains 26.66 per cent. of MgO, 8.39 per cent. of CaO and 0.11 per cent. of NiO + CoO, a percentage ratio of 0.41 NiO to 100 MgO.[24] The rock from Oakwood, Maryland,[25] with much diopside and little bronzite, contains 20.78 per cent. of MgO, 13.12 per cent. of CaO, and 0.03 per cent. of NiO + CoO, or a percentage ratio with respect to MgO of about 0.15 NiO. The rock from near Bagley Creek, Mount Diablo, California,[26] contains 19.91 per cent. of MgO, 16.32 per cent. of CaO and 0.075 per cent. of NiO or a nickel-magnesia percentage ratio of about 0.35.

It is to be noted that the rock with most bronzite carries most nickel.

Gabbros.—For the Norwegian norites the data have been given in the first part of this paper. It appears that the common anchieutectic norites (Erteli and Bamle) carry respectively 0.028 and 0.038 per cent. of NiO. In the hypersthene-rich quartz norites of Romsaas we find 0.042 per cent. NiO. In the hypersthenite-norites, especially rich in hypersthene, from Hosanger and Iveland were found 0.074 and 0.089 per cent. of NiO respectively.

[23] Clarke, *op. cit.*, p. 75.
[24] Clarke, *op. cit.*, p. 37.
[25] Clarke, *op. cit.*, p. 31.
[26] Clarke, *op. cit.*, p. 161.

The hypersthenic segregations from Bamle carry 0.113 and those from Hosanger 0.160 per cent. of NiO.

The quantity of nickel present thus increases with the hypersthene. It follows that the ordinary anchi-eutectic norites with about 45 per cent. of hypersthene must contain considerably less than 0.074 NiO and probably less than 0.042 per cent. Thus the common norites from Erteli and Bamle with 0.028 and 0.038 per cent. of NiO may be considered as normal as regards nickel content, for norites with about 45 per cent. of hypersthene.

Thirteen analyses of gabbros and norites from the United States, taken from Clarke, show from 0.01 to 0.08 per cent. of NiO, the average being about 0.03 per cent.

Olivine gabbro from Birch Lake, Minnesota,[27] contains 11.57 per cent. of MgO and 0.16 per cent. of NiO. The olivine in the same rock contains 26.86 per cent. of MgO and 0.20 per cent. of NiO. This corresponds to a percentage ratio of 0.75 NiO. The percentage ratio of NiO to MgO for the rock as a whole is about 1.5. This is probably too high and may be due to admixed pyrrhotite.

The olivine gabbro from Höiaas and the olivine norite from Erteli contain respectively 0.085 and 0.118 per cent. of NiO, corresponding to about 0.45 and 0.50 NiO to 100 MgO.

Diabases.—Seven analyses show from 0.01 to 0.10 per cent. of NiO, with an average between 0.03 and 0.04. This is probably too high for diabases as a whole.

Basalts.—Ten analyses of feldspar basalts show from 0.02 to 0.04 per cent. of NiO. In addition, one analysis shows 0.12 per cent. The arithmetical average of the eleven analyses gives 0.038 per cent. of NiO. One analysis of an olivine-rich basalt from Burns Valley, California,[28] gives 0.41 per cent. of NiO with only 8.84 per cent. of MgO. This is abnormal and suggests the presence of sulphides or metallic nickel-iron.

Five analyses of nepheline basalts and nepheline-mellilite basalts, with from 37.9 to 42.3 per cent. of SiO_2, show from 0.03

[27] Clarke, *op. cit.*, p. 55.
[28] Clarke, *op. cit.*, pp. 160–161.

to 0.06 per cent. of NiO. These rocks appear to be a little richer in nickel than the feldspar basalts with about 50 per cent. of SiO_2.

According to H. S. Washington,[29] an analcite basalt from Sardinia, with 44.85 per cent. of SiO_2 and 10.27 per cent. of MgO, contains 0.23 per cent. of NiO, which is an unusually large quantity.

Camptonites, Lamprophyres, Tinguaites, Shonkinites, Etc.—Eight analyses show from 0.02 to 0.04 per cent. of NiO and one shows 0.07 per cent. In most of these rocks the ratio is from 0.3 to 0.4 NiO to 100 MgO.

Diorites, Monzonites, Syenites, Etc.—Many analyses of these rocks, where nickel has been sought for, record a trace or none. Exceptionally as much as a tenth of one per cent. NiO has been found. In general, data for a calculation of the average content in nickel of these rocks and of effusive rocks of similar composition are lacking.

CONCLUSIONS TO BE DRAWN FROM THE FOREGOING DATA.

In the common igneous rocks some of the nickel present may be contained in pyrite, pyrrhotite, or pentlandite. In most of these rocks, however, only a very small part of the nickel can be combined in sulphides. Most of it is in the silicate minerals.

Among the silicate minerals it is the ferromagnesian silicates that carry the nickel, particularly olivine, orthorhombic and monoclinic pyroxene, amphibole and biotite. The feldspar and feldspathoids do not, so far as known, contain nickel.

Olivine, as has long been known, carries a relatively high proportion of nickel, up to half of one per cent. Generally the nickel content of olivine increases with the amount of Mg_2SiO_4 present and is less abundant in the iron-rich olivines. As will be shown later, Ni_2SiO_4 concentrates in the magma with Mg_2SiO_4. The probable ratio between MgO and NiO in the olivine of the common feldspathic igneous rocks is 100 MgO to 0.25 NiO. Such olivine (with about 30 per cent. MgO) should therefore con-

[29] *Jour. of Geol.*, vol. 22, p. 748, 1914.

tain about 0.075 per cent. of NiO. The olivine of igneous rocks rarely contains less than this. A similar relation between nickel and magnesium is found in the orthorhombic pyroxenes. The monoclinic pyroxenes, amphiboles and micas are relatively poor in nickel.

In a silicate melt nickel occurs, not as oxide, but as silicate, and on crystallization this silicate combines with the silicates of magnesium and iron. The nickel silicate in olivine and orthorhombic pyroxene shows a definite relation to the magnesium silicates (Mg_2SiO_4 and $MgSiO_3$) of these minerals. From this it may be concluded, as many investigators have assumed as a matter of course, that in olivine and orthorhombic pyroxene the nickel is a mix-crystal component and occurs as Ni_2SiO_4 and $NiSiO_3$. By analogy it may be concluded also that the nickel in monoclinic pyroxene occurs as $CaNiSi_2O_6$, or a similar compound. The compounds of nickel and cobalt, it may be recalled, are crystallographically analogous to those of magnesium, bivalent iron and manganese, zinc and cadmium, but not to those of calcium, strontium, barium, lead, or beryllium.[30]

The binary system $Mg_2SiO_4 : Fe_2SiO_4$ is a continuous mix-crystal system belonging to type I., without maximum or minimum,[31] in which Mg_2SiO_4 has a considerably higher fusion point (1890° C.) than Fe_2SiO_4 (about 1100° C.). That Ni_2SiO_4 in the ternary system $Mg_2SiO_4 : Fe_2SiO_4 : Ni_2SiO_4$ should be concentrated with the Mg_2SiO_4 must be because Ni_2SiO_4 has a rather high fusion point, certainly higher than that of Fe_2SiO_4. Analogous reasoning may also be applied to the relations at high temperature between $MgSiO_3$, $FeSiO_3$, and $NiSiO_3$ and probably also to those between $CaMgSi_2O_6$, $CaFeSi_2O_6$, and $CaNiSi_2O_6$.

From the analyses it appears that with the same proportion of iron silicate, olivine generally contains more nickel than orthorhombic pyroxene and orthorhombic pyroxene more than monoclinic pyroxene, amphibole, or biotite.

[30] See Groth, B., "Elemente der physikalischen und chemischen Krystallographie," pp. 298–300, 1921.

[31] Vogt, J. H. L., *Jour. of Geol.*, vol. 1, pp. 521–523 and Fig. 22, 1921.

For a saxonite from the Riddles quadrangle, Oregon, composed predominantly of olivine with less than one third enstatite or bronzite, the following data are available:

	Total Rock Per Cent. of NiO.	Olivine Per Cent. of NiO.	Bronzite Per Cent. of NiO.
v. Foullon[32]	0.27	0.32	0.05
Clarke[33]	0.10	0.26	——

In spite of some uncertainty attaching to some of these determinations, it may fairly be concluded that in the crystallization of a given magma the olivine will take up more nickel than the orthorhombic pyroxene. This must be partly due to the fact that the olivine is an orthosilicate and so contains more RO base than the pyroxenes. Thus if we take olivine as a basis and take orthorhombic and monoclinic pyroxene with the same stoichiometric percentage of iron silicate, namely 29.85, and if, further, we assume the same percentage, namely 0.15, for the corresponding nickel silicates ($NiSiO_4$, $NiSO_3$ and $CaNiSi_2O_6$), then we get the following result, the figures being percentages.

	MgO.	NiO.	100 MgO ÷ NiO.
Olivine	35.2	0.139	0.40
Orthorhombic pyroxene	25.5	0.101	0.40
Diopside	12.4	0.049	0.40

Actually, the proportion of nickel in the olivine is generally larger than is called for by the above assumption of identical stoichiometric proportions of the nickel silicates.

The concentration of nickel during the crystallization of magmas must, as maintained by several investigators, be explained as a result of crystallization-differentiation.[34]

[32] Foullon, H. B. v., *Jahrb. d. K. K. geol. Reichanstalt,* 1892.

[33] Clarke, F. W., *op. cit.,* p. 166.

[34] See my paper in the *Journal of Geology* on "The Physical Chemistry of the Crystallization and the Magmatic Differentiation of Igneous Rocks," where I argue that the minerals that sink in the deep-seated magma basins are generally wholly dissolved. Thus, for example, the anorthosites were not, as supposed by Bowen, formed by the accumulation of solid crystals of plagioclase but crystallized from an entirely liquid magma. J. H. L. V.

When at the beginning of crystallization in a deep-seated magma basin one or more minerals separate and become segregated and removed by difference in density, we get two different magmas, to one of which the constituents of these minerals have been added and from the other of which they have been taken away. The part to which they have been added I propose to distinguish as a *proto-enriched* magma. The part from which the crystals have been subtracted and which consequently has been enriched in the eutectic that for each particular case is decisive for crystallization, I propose to call an *eutect-enriched* magma.

With extreme magmatic differentiation there results, as I have previously maintained,[35] on the one hand, an anchi-monomineralic (*i.e.*, almost one-mineral) magma (dunite, bronzite rock, anorthosite, etc.) and, on the other hand, an anchi-eutectic magma (common norites, gabbros, syenites, granites). The eutectic granites containing about 75 per cent. SiO_2 represent the end result of the entire process of differentiation.

When olivine crystallizes from a magma, the first mix-crystals to separate contain a relatively large proportion of the constituent Mg_2SiO_4, with very high melting point, and a relatively small proportion of the constituent Fe_2SiO_4, with a comparatively low melting point. As crystallization-differentiation advances, the more Mg_2SiO_4 and the less Fe_2SiO_4 are concentrated with the olivine, down to a point where the olivine contains only about 7 per cent. of Fe_2SiO_4. Ni_2SiO_4 is concentrated with the Mg_2SiO_4 in the olivine. These conclusions are summarized in tabular form below.

TABLE V.

AVERAGE STOICHIOMETRIC COMPOSITION OF OLIVINES.

	Mg_2SiO_4.	Fe_2SiO_4.	Ni_2SiO_4.
In gabbros, norites, etc.	70–75	25–30	0.16–0.25
In peridotitic rocks:			
with 35–50 per cent. of olivine	75	25	0.16–0.25
with 50–60 per cent. of olivine	75–80	20–25	0.20–0.45
with 60–70 per cent. of olivine	80–84	16–20	0.20–0.45
with 90–95 per cent. of olivine	91–92	8– 9	0.30–0.60

[35] Vogt, J. H. L., "Ueber anchi-monomineralische und anchi-eutektische Eruptivgesteine, Kristiania," *Vidensk. Selsk.*, 1908, and *Norwegian Geological Journal*, 1905.

Orthorhombic pyroxene behaves similarly, although here, of course, we deal with metasilicates instead of orthosilicates.

The following table shows the relation of the percentage ratio (100 MgO ÷ nNiO) to the analyses of olivine and olivinitic rocks on the one hand and orthopyroxenic rocks[36] on the other.

100 MgO - nNiO.	Olivine and Rocks rich in Olivine. No. of Analyses.	Orthorhombic Pyroxene and Rocks rich in Hypersthene. No. of Analyses.
Above 1.00		
(Maximum 1.15)	4 (?)	
0.90–0.99	3	
0.80–0.89	3	1
0.70–0.79	4	
0.60–0.69	4	1
0.50–0.59	3	3
0.40–0.49	9	2
0.30–0.39	10	2
0.25–0.29	1	1

In spite of many probable inaccuracies, this table is instructive. Most of the determinations on the olivinitic rocks which give a nickel ratio from 0.6 to 1.0 have been made on iron-poor olivine, dunite, saxonite, etc., that is, on rocks that are comparatively rare and occur in relatively small masses. The ferruginous olivines of the commoner rocks give ratios between 0.35 and 0.50. Hypersthene and the ordinary norites generally give ratios between 0.25 and 0.55. For the monoclinic pyroxenes, the few determinations available show from 0.3 to 0.4 of NiO to 100 MgO. For amphibole and biotite the ratios are perhaps a little lower. The ratio for the ferromagnesian silicates as a whole lies between 0.4 and 0.3. The average is probably about 0.35.

THE AVERAGE CONTENT IN NICKEL OF THE IGNEOUS ROCKS.

For the peridotites, the estimated average is 0.18 per cent. of NiO or 0.14 per cent Ni. For the pyroxenites, the average is

[36] The websterite with 0.11 per cent. nickel mentioned on page 321 is included but not the other two websterites there listed.

about 0.08 per cent. Ni. The average for all facies of the norites is calculated to be 0.035 per cent. Ni. For the olivine-free gabbros and for diabases, basalts, and closely related rocks, the estimate is 0.030 per cent. of Ni. For syenites, monzonites, diorites, etc., with their corresponding dike and effusive rocks, the estimate, based on a few determinations and on their MgO contents, is 0.006 per cent. of NiO. The granites contain very little nickel, probably less than 0.001 per cent. It is practically all in the biotite.

The following table is an attempt to arrive at a general average for the deep-seated or plutonic igneous rocks by taking into consideration the relative abundance of each rock group.

Rock Groups.	Relative Mass.	Per Cent. of Ni in Each Group.	Per Cent. of Ni for Plutonic Rocks as a Whole.
Peridotites, pyroxenites, etc.	0.5	0.120	0.0006
Gabbros, norites, etc.	25.0	0.030	0.0075
Syenites, monzonites, diorites, anorthosites, etc.	15.0	0.006	0.0009
Granites	60.0	0.0005	0.0003
All plutonic rocks			0.0093

The greater part of the nickel in the plutonic igneous rocks, from .8 to .9, is present in the gabbroitic rocks. Among these the norites are generally richer in nickel than the diallage gabbros.

Nickel, cobalt, and chromium are elements which have been concentrated in the basic rocks, so that very little has been left in the residual anchi-eutectic magma, which has crystallized as granitic. In a parent magma with about 60 per cent. of SiO_2, the small amount of Cr_2O_3 present will not enter into chromium-spinel (picotite) or chromite, but goes into the pyroxene-minerals. With the magmatic concentration of these, some Cr_2O_3 will be added to the proto-enriched magma. In such a magma, somewhat basic and rather rich in MgO or MgO + FeO, conditions are present for the formation of chromium-spinel (picotite) or

[36a] In a previous treatise (Zeits. für prakt. Geol. 1898, pp. 236–237) I have calculated the average nickel content in the igneous rocks as 0.005 or 0.010 p. c.

of this and chromite, both of which, even when present in quite inconsiderable quantities,[37] begin to crystallize at a very early stage. From this moment there may take place a magmatic concentration of chromium-spinel, plus chromite, together with Mg, Fe-silicate (olivine, pyroxene, etc.), this concentration being due to crystallization-differentiation. In this way there may result a magma fairly rich in RCr_2O_4—or $R(Cr, Al, Fe)_2O_4$—and within this magma again there may be formed special segregations of chromite (the chromite deposits) by a renewed process of magmatic differentiation.

The quantity of nickel in ore deposits is closely related to the quantity of nickel in the various igneous rocks.

The garnierite deposits, formed by secondary processes near the surface, occur only in peridotites and in serpentine derived from these.

The nickel-pyrrhotite deposits are, as is well known, nearly all associated with norites, although some small but rich deposits occur in peridotites. Similar deposits, but so far as known of relatively very low grade, are also known in some diallagic gabbro and very rarely in anorthosites, but never in the siliceous rocks.

Fissure veins characterized by relatively abundant nickel-cobalt-arsenic ores (chloanthite, niccolite, cobaltglance, etc.) are, where they occur in or near eruptive rocks, associated with diabase or similar rocks (*e.g.,* Nanzenbach in Nassau; Temiskaming, in Ontario, with native silver).

On the other hand, ore deposits associated with granite, such as the tin veins, many gold-quartz and copper veins, and many contact deposits, are characterized throughout by little or no nickel or cobalt. It is specially to be noted that in granitic contact deposits are found iron, copper, lead, zinc, silver, and gold, but only traces of nickel and cobalt.

Another method for calculating the average contents of nickel in the rocks is the following:

The igneous rocks contain, according to F. W. Clarke,[38] an

[37] *Jour. of Geol.,* 1921, pp. 322 and 635.

[38] "The Data of Geochemistry," U. S. G. S. Bull. No. 695, 1920.

average of 3.74 per cent. MgO. We have seen that 100 parts by weight of MgO is generally accompanied by about 0.35 part by weight of NiO, corresponding to 0.275 part by weight of Ni. This gives $3.74 \times 0.275 \times 0.01 = 0.010$ per cent. of nickel in the rocks. To this should be added the small quantity of nickel that may be in the sulphides. The igneous rocks contain on the average 0.10 per cent. of sulphur which, calculated as pyrite, gives about 0.19 per cent. pyrite or, as pyrrhotite, about 0.26 per cent. pyrrhotite. Pyrite in the igneous rocks is considerably more abundant than pyrrhotite. We may estimate about 0.17 per cent. of pyrite (practically free from nickel) and, at most, only about 0.02 per cent. pyrrhotite, which generally contains but little nickel. Thus the sulphides contain so little nickel as to be negligible.

F. W. Clarke, as is well known, has used still another method. He has taken the mean of all analyses of igneous rocks at hand and from this has calculated an average of 0.020 per cent. nickel.[39] He remarks, however, that the figure is probably a little too high.

The first method that I have followed is open to error, but it is correct in principle and must, when the relative distribution of the igneous rocks is better known, lead to a reliable result. The second method used also offers many advantages. There is, moreover, an astonishingly close agreement between Clarke's 0.020 per cent., which must be considerably too high, and the result reached by me, through two different methods, namely 0.010 per cent. It is, of course, an accident that these two last-mentioned methods give exactly the same number.

As will be shown in the following part of this paper, rocks carry, on the average, about $\frac{1}{12}$ as much cobalt as nickel.

[39] The Data of Geochemistry and previous studies. In 262 analyses of igneous rocks made in the laboratory of the United States Geological Survey was found an average of 0.0274 per cent. of nickel oxide, equal to 0.021 per cent. Ni. Since the 262 analyses may include a relatively large number of rare rocks, such as dunites, saxonites, etc., with a high content of nickel, and nickel has not been sought for in common analyses of granite, etc., with only a trace of nickel (0.0005 per cent. or less), Clarke's estimate of 0.021 per cent. for the average nickel content in the igneous rocks may be not only a little, but much too high.

I thus conclude that the igneous rocks as a whole contain about 0.010 per cent. of nickel (Ni) and 0.001 (or 0.0008) per cent. of cobalt (Co).

ON THE RELATION BETWEEN THE COMPOSITION OF BASIC IGNEOUS ROCKS AND THE TENOR IN NICKEL OF ASSOCIATED SEGREGATIONS OF NICKEL-PYRRHOTITE.[40]

INTRODUCTORY REMARKS.

About thirty years ago[41] I showed that the sulphidic ore deposits here described were formed by magmatic differentiation. Referring partly to my original treatise (1893) and partly to subsequent papers, especially "Die Sulfid-Silikatschmelzlösungen,"[42] I shall try to explain the details of the process. This view has been substantiated by numerous later investigators, but has also been subjected to some criticism or doubt. As I am quite sure that the explanation is in the main correct, I find it superfluous to review, at this point, the arguments for its justification.

The solubility of the sulphides in silicate melts or in magmas is a function of the composition of the magma—as the solubility in general decreases with the acidity of the melt or the magma—and of the temperature. The magma can dissolve but little FeS_2. This mineral, therefore, separates at a very early stage in the solidification of the rock, viz., at a temperature which generally lies lower than the fusion point of the pyrite (under high pressure). That is, when the limit of the solubility is reached, the pyrite separates as a crystalline phase.

On the other hand, in a noritic magma, where the dissolved sulphide is essentially RS, mainly FeS, a considerable quantity of the sulphide, even over 1 per cent. of RS, may remain dissolved at a temperature about 1300° C.[43] If there is rela-

[40] I use the term nickel-pyrrhotite to designate the nickel-carrying pyrrhotite, *i.e.*, pyrrhotite with pentlandite and some chalcopyrite and pyrite.

[41] *Zeitschr. für praktische Geologie*, 1893, and a previous paper in the Norwegian language, 1892.

[42] *Norsk. Geologisk Tidsskrift*, IV., 1917.

[43] Here, and in what follows, the temperature is computed to the pressure of one atmosphere, as the increase of the fusion point of the minerals due to

tively little RS (FeS, etc.) present, this will remain dissolved in the magma after the crystallization of the silicate minerals has begun (at about 1275°). The sulphide, mainly FeS, will thus first begin to separate after crystallization of the silicate minerals (at about 1250–1275°) has made some progress. As the melting point of pyrrhotite, with accompanying sulphides, lies somewhat below 1200°, the FeS, which may contain small quantities of other sulphides, will be segregated in the liquid state. Thus we find that the pyrrhotite of the common norites, with ¼ or ½ per cent. pyrrhotite, belongs to the last stage of solidification (see Figs. 46 and 47 in my treatise in *Jour. of Geol.*, 1921, p. 643).

Under certain circumstances this segregated liquid sulphide may be squeezed out as local enrichments. With higher original contents of dissolved sulphides, the segregation of the sulphides, mainly FeS, will begin partly before and partly coincidentally with the incipient crystallization of the silicate minerals. The segregated liquid sulphide, FeS with a little FeS_2 and some Ni, Co, and Cu sulphide, will, because of its gravity, sink in the magma, in many cases to the bottom, and will accumulate under certain conditions.

In hypersthenite-norites, with only 20–40 per cent. of plagioclase, and in anchi-eutectic norites, with some surplus of hypersthene above the eutectic hypersthene-plagioclase boundary (see Figs. 10–13 and pp. 432–443 in *Jour. of Geol.*, 1921), some hypersthene will in many cases crystallize coincidentally with the segregation of the liquid sulphide. At a certain stage we may thus get a magma containing solid crystals of hypersthene and drops of liquid sulphide, both of which, on account of their higher specific gravity, will sink to the bottom. The rather common deposits of pyrrhotite-hypersthenite in certain Norwegian localities may be explained in this way (see Figs. 40–43 in *Jour. of Geol.*, 1921, pp. 640–641).

pressure is so small that it may almost be disregarded. The indirect influence of pressure in increasing the dissolved quantity of the light volatile compounds (H_2O, etc.), which again involves a lowering of the temperature of crystallization, is, in the present case, of subordinate importance.

In anchi-eutectic norites with a surplus of plagioclase (labradorite) above the eutectic hypersthene-labradorite boundary, we may analogously get deposits consisting mainly of pyrrhotite and labradorite (see Figs. 44 and 45 in *Jour. of Geol.*, 1921, p. 642). On account of the chemical composition of the sulphide-melt the principal sulphide to form is pyrrhotite (FeS with some FeS_2 dissolved in solid phase) with some pentlandite and chalcopyrite and usually a little pyrite, ilmenite, and magnetite. The sequence of crystallization is (1) ilmenite and magnetite, (2) the entire quantity of pyrite, (3) if the quantity of pentlandite and chalcopyrite is not unusually high, only pyrrhotite, and (4) pyrrhotite with pentlandite and chalcopyrite. Chalcopyrite especially begins to crystallize at a relatively late stage.

According to determinations at the Geophysical Laboratory of the Carnegie Institution, Washington, the fusion-point of pyrrhotite is between 1183° and 1187°. The temperature of crystallization must be somewhat lowered by admixture of pentlandite and chalcopyrite, but on the other hand, ilmenite, magnetite, and pyrite crystallize a little earlier, accordingly at a little higher temperature than the pyrrhotite. As the three last-named components are present only in small quantities, however, they can raise the crystallization point but a few degrees. The crystallization of the sulphides will thus begin a little below 1200° and be complete at 1150° or probably somewhat below that temperature. The sulphides will thus exist in the liquid phase after the silicate mother rock has partly, or in some rocks completely, solidified.

The deposits of nickel-pyrrhotite are not accompanied by pneumatolytic minerals. They thus appear in contrast with the deposits of pyrite of the Sulitjelma, Røros, and Tinto type, to be formed from dry or almost dry melts.

In flat-lying intrusive rock masses the sulphides commonly will be accumulated near the bottom of the mass (*e.g.*, many deposits in the Sudbury district, and at Espedalen, Hosanger, Eiteraadalen in Raandalen, Meinkjär in Bamle, etc., in Norway).

The molten sulphides are extremely fluid and often form mar-

ginal injections, such as the Sudbury offset-deposits, which commonly are characterized by a brecciated structure.

During the solidification of the sulphidic magma a special crystallization-differentiation has often taken place, and the still very fluid residual part of the magma, enriched in copper, has been squeezed out separately. The extremely small contents of platinum-metals associated with these deposits have been concentrated in the residual magma with the chalcopyrite. The squeezing out of this residual magma thus may produce offset-deposits characterized by much copper and nickel and by an exceptionally high proportion of platinum-metals, especially platinum and palladium (*e.g.*, Vermilion in the Sudbury district).

Th. Vogt in his monograph on the Sulitjelma deposits,[44] which also are sulphidic segregations, but were formed under other physico-chemical conditions than those here considered, has used this squeezing hypothesis to explain several very important phenomena.

Segregations of nickel-pyrrhotite are very common in norites, and in Norway alone, inclusive of some rather small deposits, 37 separate bodies of norite (and peridotite) are known to be accompanied by nickel-pyrrhotite. The deposits that are associated with quite small bodies of norite and peridotite are themselves of very small dimensions. The large deposits always accompany large intrusive masses, especially of norite. However, it must not be concluded that all large norite masses must be accompanied by large deposits of nickel pyrrhotite, or that the deposits which accompany large norite bodies are themselves necessarily large.

I shall now review the average percentage of nickel in the total sulphides of a number of Norwegian deposits and the mineralogical and chemical composition of the mother-rock at these localities. The largest deposit in Sweden, that at Klefva, will also be considered, and also, for special reasons, that at Alexo in Canada, in peridotite. Within each deposit the percentage of nickel which is in the mixture of sulphides (pyrrhotite, pentlandite, chalcopyrite and pyrite, with occasionally a negligible amount

[44] In press as a publication of the Norwegian Geological Survey.

of galena, blende, etc.) varies within fairly wide limits. Thus in one mine between 2.25 to 3.5 per cent.; in another, between 3.5 and 5.5 per cent.; and in a third, between 4.5 and 10 per cent. Consequently, to determine the average percentage of nickel many analyses are needed, especially of large representative samples. Not only nickel and copper should be determined, but also sulphur, so that the total quantity of sulphides can be calculated. In this calculation I have assumed that the mixture of the sulphides contains, on the average, 38 per cent. of sulphur. A check on the calculations is supplied by the quantity of nickel in the "first matte."[45]

The amount of chalcopyrite in the sulphides, on account of crystallization-differentiation, is subject to great variation. The proportion between nickel and copper therefore is best determined by the analyses of the matte, especially the bessemer matte.

In the Norwegian deposits the nickel ore generally consists of from 25 to 50 per cent. of sulphides, the remainder being silicates. A considerable part of the nickel may occur in the silicates, but naturally it is a great advantage to have as much of the nickel as possible in the sulphides.

DEPOSITS IN PERIDOTITES.

Alexo.—The Alexo mine is in Dundonald township, in northern Ontario.[46] In a body of serpentinized peridotite, which to judge from the description is rather poor in iron, occurs a common marginal deposit of sulphides which dips at about 60°, under the serpentine. Up to the end of the year 1916, the total output amounted to 34,650 tons of ore, which averaged over 4 per cent. nickel. Some samples gave as much as 11.46 per cent. of nickel. Compared with typical Sudbury ore there is much less copper. The average content of the pure sulphides appears

[45] When the ore is melted without previous roasting and without admixture of slags containing nickel, etc., the "first matte" as a rule contains 1.25 times as much nickel as the total sulphides.

[46] Uglow, W. L., *Jour. Can. Min. Inst.*, vol. 14, 1911. A. P. Coleman, Econ. Geol., 5, 1910, "The Nickel Industry," 1913. Short remarks in the Report of the Royal Ontario Nickel Commission, 1917.

to have been about 8 per cent. of nickel, with relatively little copper.

Bruvand.—Within a great body of norite[47] there occurs at Bruvand, near Balangen, Ofoten, Norway, a mass of peridotite rather poor in iron and very rich in olivine. It consists of about 85 per cent., or even 90 per cent. of olivine (with about 86 per cent. of Mg_2SiO_4 to 14 per cent. of Fe_2SiO_4), with bronzite, some amphibole, and a little picotite. The composition of the rock is according to a partial analysis.

	Per Cent.
SiO_2	41.2
Al_2O_3	3.7
Fe_2O_3, FeO	13.7
MgO	39.9
CaO	1.5

This peridotite, which is almost wholly fresh and not the least serpentinized, carries locally from 7.5 to 8 per cent. of sulphides (see Figs. 38 and 39 in *Jour. of Geol.*, 1921, p. 640), viz., pyrrhotite, pentlandite, and chalcopyrite. The sulphides carry about 7 per cent. of nickel, with nearly 25 parts of copper to 100 parts of nickel by weight.

A mineralogically similar rock from the same district, according to Foslie, has the following composition:

	Per Cent.
SiO_2	41.74
Al_2O_3	2.87
Fe_2O_3	2.96
FeO	10.66
MgO	38.70
CaO	1.48
S	0.12
Ni	0.14

He also reports the presence of a little TiO_2, MnO, Cr_2O_3, Na_2O, and K_2O.

[47] S. Foslie, Raana Noritfelt. Norges geol. Unders. Aarbok, 1920.

DEPOSITS IN OLIVINITIC PYROXENITE.

Espedalen.—In Espedalen, Norway, within an area of about 150 square kilometers of labradorite-rock, occur a number of segregations partly of norite and partly of an olivine-pyroxene rock.[48]

The last-mentioned rock, which forms small bodies up to about 1 kilometer in length, is in at least 7 places accompanied by deposits of nickel-pyrrhotite. These occur mainly as typical marginal deposits at the base of the olivine-pyroxene rocks. The dip is generally less than 30°, but at one mine is 80°.

Here two separate processes of magmatic differentiation have taken place successively. From the original magma was first segregated an olivine-pyroxene magma, and from this was segregated a nickel-pyrrhotite magma by the sinking of the sulphides to the lower part of the magma.

The olivine-bearing pyroxenite consists of moderately ferriferous diallage, hypersthene, and olivine, with occasionally a little brown amphibole, and exceptionally an extremely small quantity of plagioclase. The hypersthene and the olivine are both optically negative, but with a very large axial angle, between 85° and 90°. The two minerals thus contain 20 per cent. or a little more than 20 per cent. $FeSiO_3$ and Fe_2SiO_4 respectively. This rock is consequently richer in iron and considerably poorer in magnesia than the rock from Bruvand just described. The proportion between the three principal minerals varies widely from place to place. In places the rock is over half olivine, at other places olivine is nearly or entirely lacking. Similar variation occurs in the proportion between diallage and hypersthene. On the whole, however, the three minerals are present in nearly equal proportions and the average composition of the rock may be computed as follows:

[48] V. M. Goldschmidt, "Übersicht der Eruptivgesteine im kaledonische Gebirge Zwischen Stavanger und Trondhjem." *Kristiania Vidensk. Selsk.*, 1916. C. W. Carstens, "Norwegian Peridotites, II.," *Norsk. Geol. Tidskr.*, V., 1918.

	Per Cent.
SiO_2	46.
TiO_2	0.3
Al_2O_3	4.
Fe_2O_3	3.
FeO	12.4
MgO	27.
CaO	7.
Na_2O	0.3

Some of the ore is fairly rich in sulphides, but part of it contains much diallage and hypersthene, with occasionally some olivine and amphibole.

The mines were first worked for copper, but in 1843 Th. Scheerer, professor at the University of Christiania, discovered the new mineral "iron-nickel-pyrite," later named pentlandite, in samples from Espedalen. Whereupon the mines for some years were worked for nickel. From 50,000 to 100,000 tons of ore have been mined.

As shown by a detailed investigation, the content of nickel in the sulphides averages about 4.5 per cent. Some samples, especially rich in pentlandite, contain from 7 to 10 per cent. of nickel, showing that there was considerable magmatic differentiation in the sulphide magma. With every 100 parts of nickel there are 40 to 50 parts of copper.

DEPOSITS IN NORITE AND HYPERSTHENITE-NORITE.

Hosanger.—The hypersthenite-norite of Hosanger, Norway, with a length of about 2⅓ kilometers, and maximum breadth of 0.7 kilometer, forms a flat-lying laccolith (or phacolith) of varying thickness. The contact with the crystalline schists, both at the top and bottom of the laccolith, dips from 15° to 25°. The boundary between the hypersthenite-norite and the underlying schist is hummocky. In the adjacent schists occur at least 5 smaller lens-shaped masses of the intrusive rock.

The rock is characterized (see analysis No. 6 and Table IV) by unusually abundant hypersthene with other ferromagnesian silicates. The plagioclase, a basic labradorite, generally forms about

20 per cent. of the rock, with a range from 10 to 40 per cent. In some places occur segregations free from plagioclase. Some of these are olivine-free hypersthene-diallage rock with some amphibole and biotite (analysis No. 7) and some are olivine-carrying hypersthene-diallage rock (see Fig. 25 in *Jour. of Geol.*, 1921, p. 530). The common hypersthenite-norite (analysis 6) carries 0.058 per cent. of nickel, and a segregation (No. 7) of olivine-free hypersthene-diallage rock contains 0.126 per cent. of nickel.

At three places, at the lower contact of the igneous rock, occur large deposits of nickel-pyrrhotite. At least one of these must be classed among the largest deposits of this kind that have been found in Norway. The ore, which is more or less mixed with hypersthene, diallage, amphibole, and biotite, with occasionally a little plagioclase, carries up to 60 per cent. of sulphides. Most of the ore, however, contains much less and might be classed as a pyrrhotite-hypersthenite.

The tenor of the sulphides ranges from 5 per cent. to 10 per cent. The average at one of the mines lies between 6 and 6.5 per cent., and at another between 6.5 and 7 per cent. The proportion of nickel to copper is as 3 to 1.

Beiern.—In a very small mass of gabbroitic rock, with an area of perhaps 600 square meters, in Beiern, Norway, there occurs a little marginal deposit with a dip of about 75° beneath the gabbro. The original pyroxene-mineral of the rock has been entirely changed to amphibole. As the rock has exactly the same character as the uralitic rocks that in other localities are derived from norite, we may take it for granted that the rock at Beiern is an altered norite. It contains only 35 to 40 per cent. of labradorite. The primary rock thus must have been a norite poor in plagioclase or a hypersthenite-norite.

In the ore from the small mine, which has produced from 650 to 700 tons in all, I recognized in 1891 [49] "iron-nickel-pyrite" (pentlandite), which contains 33.34 per cent. of Ni and 0.46 per cent. of Co.

[49] See "Geol. Føren. Førh.," B. XIV., 1892.

The ore body is thin, not over 0.7 meter in thickness, but very rich in nickel. It averages from 5 to 6 per cent. of nickel in lots containing from 15 to 20 per cent. of silicates. From several representative analyses, the content of nickel in the sulphides alone is calculated to be 6.5 or 7 per cent. The ratio of nickel to copper is as 5 to 1.

Flaad.—At Flaad in Evje and in the adjoining parish of Iveland occurs a very large mass of gabbroitic rock or, perhaps, a number of separate masses, as the field has not yet been mapped in detail.

At Mølland, in Iveland, the rock is a hypersthenite-norite (see analysis No. 9). In the environs of Flaad in Evje the original pyroxene of the rock has been entirely changed to amphibole. The rock appears to have been a norite fairly rich in hypersthene, although with less hypersthene than the rock of Iveland (No. 9).

At the Flaad mine is the largest deposit of nickel-pyrrhotite that yet has been found in Norway. The mine, which has a depth of 232 m., has up to date produced about 310,000 tons ore.[50]

The average nickel content of the sulphides is from 4 to 4.5 per cent., with 66 parts of copper to 100 parts of nickel.

Bamle.—In Bamle, Norway, along a zone of about 4⅓ km. in length, are at least 12 small bodies of norite. At least 10 of these are accompanied by deposits of nickel-pyrrhotite, which for the most part are very small, however. The largest two of the norite bodies that contain nickel ore have areas of about 4,000 and 3,000 square meters, at Meinkjaer[52] and Nysten. Some kilometers outside the zone mentioned lies a larger norite mass, at Skougen, with a length of about 3.5 km. and a width of about 2 km.

The analyzed norite from Skougen (No. 4) consists of about 45 per cent. of hypersthene, 4 per cent. of biotite, and 49 per cent. of labradorite (Ab_2An_3), with a little ilmenite. It thus has some excess of hypersthene above the hypersthene : labradorite

[50] For geologic details see Figs. 193–194, p. 321, Beyschlag-Vogt-Krusch, "Die Erzlagerstätten," Vol. I., 1914.

[52] See map and profile in Beyschlag-Krusch-Vogt, "Die Erzlagerstätten," I., 1914, p. 319.

eutectic limit. A number of thin sections of norite, from the various smaller bodies, especially those of Meinkjaer and Nysten, show nearly the same composition. Some varieties of the rock contain only 20 per cent. of labradorite and are intermediate between the normal rock and the plagioclase-free segregations previously mentioned (analysis No. 5), consisting of hypersthene and some amphibole, biotite, etc. The norite and the segregation show respectively 0.038 and 0.113 per cent. of NiO (analyses No. 4 and 5). The mines have produced about 50,000 tons of ore.

The sulphides at one of the two principal mines carry from 2.75 to 6.3 per cent. of nickel. The average content is about 4 per cent. At the other mine the range is from 2.75 per cent. to 5.2 per cent., the average being between 3.5 and 4 per cent. The calculated average for both mines is from 3.75 to 4 per cent. of nickel, with 45 parts of copper to each 100 parts of nickel.

Romsaas.—At Romsaas, Norway, occurs a small area, about 65,000 square meters in extent, of quartz-norite (analysis No. 8b) which locally shows orbicular structure (see map and profile in Beyschlag-Vogt-Krusch, *op. cit.*, Fig. 191, p. 319). At some places, fairly near its margin, the quartz-norite carries some sulphide, with "schlieren," carrying up to 50 per cent. of nickel-pyrrhotite, the remainder being hypersthene (see *Jour. of Geol.*, 1921, Figs. 40 and 42, pp. 640–641). In the years 1870 to 1876 there was produced 11,300 tons of ore.

The sulphides contain, according to old analyses, from 3.5 to 3.75 per cent. of nickel, with about 40 parts of copper to each 100 parts of nickel.

Skjaekerdalen.—At Skjaekerdalen, Norway, is a norite mass, about 2 kilometers in length, of somewhat varied petrographic character. Much of the rock is a diallage-carrying norite (see Figs. 20 and 21 in *Jour. of Geol.*, 1921, p. 520), which in places contains some olivine.

While the sulphides at most of the other mines in Norway are especially associated with hypersthene, in Skjaekerdalen they occur with labradorite (see Figs. 44 and 45 in *Jour. of Geol.*, 1921, p. 642). There was therefore a concentration of lab-

radorite coincidentally with the sulphides, which must be due to the fact that the magma contained an excess of the labradorite molecule above the eutectic proportions of labradorite, on the one hand, and hypersthene and diallage on the other. From 1876 to 1891 18,741 tons of ore were produced.

The pyrrhotite, with microscopic pentlandite, from the principal mine contains between 3.8 and 4.2 per cent. of Ni + Co, which corresponds to about 3.6 per cent. of nickel for the total sulphides. At the other smaller deposits the percentage of nickel was somewhat lower. The average for all deposits within the field is estimated at about 3.5 per cent. of nickel.

Erteli.—At Erteli, Norway, in an area of about 0.2 square kilometer (see map, Fig. 192, in Beyschlag-Vogt-Krusch, *op. cit.*, p. 320), are several closely related varieties of eruptive rocks, mainly norite and olivine-norite (Nos. 1 and 2). In extremely small quantity occurs also an amphibole-peridotite (analysis No. 3). The ore deposits, which have produced about 280,000 tons of ore, occur near the contact between the olivine-free norite and the surrounding crystalline schists.

The norite analyzed (analysis No. 1) consists of about 44 per cent. of hypersthene (with about 32 per cent. $FeSiO_3$) and 55 per cent. of labradorite (about Ab_3An_7), with 1 per cent. of magnetite, ilmenite, etc. There is no biotite or diallage and many thin sections of the rock show these minerals to be generally lacking. A diallage-gabbro, however, occurs locally. In several thin sections of the norite a little quartz, from 1 to 5 per cent., was noted. The average composition of the norite as a whole may be estimated as 43 per cent. of hypersthene, 54 per cent. of labradorite, 2 per cent. of quartz, and 1 per cent. of magnetite, ilmenite, etc. This norite, unlike the norites of Hosanger, Iveland, Romsaas, Bamle, Høiaasen, etc., has a hyperitic or ophitic structure, indicating that the plagioclase began to crystallize at a very early stage. This is connected with the fact that the norite from Erteli carries more plagioclase than the norite from the other Norwegian localities mentioned.

At the principal mine, which has a depth of about 300 meters,

the ore forms a typical marginal breccia-lode, partly at the contact between the norite and the crystalline schists and partly extending for some meters into the schists.

The sulphides as a whole contain from 2.5 to 2.75 per cent. of nickel, with 74 parts of copper to 100 parts of nickel. The percentage of nickel in the sulphides is thus lower than in the previously described Norwegian deposits, but the sulphides at Erteli are, on the other hand, less mixed with silicates than in the other deposits.

Senjen.—The total output of the Senjen deposit, Norway, amounted to 109,000 tons of ore between 1872 and 1886. The total sulphides carried about 3.5 per cent. of nickel, with about 40 parts of copper to 100 parts of nickel. The deposit occurs in a norite, which, according to samples sent me, is in some places accompanied by an amphibole peridotite. Petrographical details of the rock are not available.

Graagalten.—At Graagalten, in Sigdal, Norway, about 8,000 tons of ore, with about 2.5 per cent. of nickel in the total sulphides and 75 to 80 parts of copper to 100 parts of nickel, were produced from 1874 to 1877. The original pyroxenes are completely converted to uralitic amphibole, so that the original character of the rock cannot be determined. It seems to have been a common norite relatively rich in plagioclase.

Other Norwegian Deposits.—Besides the deposits just described, some others are known, but have not been productively mined. So far as known, all these are of small dimensions. The rock at all the deposits I have visited or from which I have samples is a norite.

The sulphides as a whole in these probably small deposits carry from 2.5 per cent. to 6 per cent. of nickel.

Worthy of separate mention is the deposit at Fæö. This is a lenticular "dike" consisting of almost pure sulphide, with about 2 per cent. of nickel and 2 per cent. of copper in the ore, and with from 2.4 to 2.5 per cent. of nickel and 2.4 to 2.5 per cent. of copper in the sulphides as a whole. This deposit occurs in a saussuritic gabbroitic rock and is to be considered as a nickelif-

erous member of the Sulitjelma-Røros group of deposits, and does not belong geologically with the group of which Sudbury, Erteli, Bamle, Klefva, etc., are typical representatives.

Klefva.—At Klefva, in Småland, is the largest and best-known deposit of nickel-pyrrhotite in Sweden. It occurs within a norite mass of about 2 square kilometers in area. The rock is a diallagic and quartzose norite, with hyperitic structure, which consists of nearly 40 per cent. of ferromagnesian silicates, and about 60 per cent. of labradorite, with a little quartz, apatite, iron oxides and pyrite. The ferromagnesian silicates comprise about 25 per cent. of hypersthene (with about 35 per cent. of $FeSiO_3$), 10 per cent. of diallage, and 5 per cent. of biotite and amphibole, in terms of the whole rock. The rock norite from Klefva is estimated to contain about 8 per cent. of MgO and about 52 per cent. of SiO_2.

The total output of the mine amounts to from 200,000 to 250,000 tons of ore. Up to about 1840 the ore was smelted for copper only. The ore is a pyrrhotite-norite, in which the sulphides as a whole average about 2.6 per cent. of nickel, with from 55 to 60 parts of copper to 100 parts of nickel.

Sudbury.—The Sudbury deposits at Sudbury, Canada, have much larger dimensions than the Norwegian, Swedish, and other geologically analogous deposits, such as those of Insiswa in Southern Africa, Varallo in Piedmont, Italy, St. Blasien in Schwarzwald, Baden, and the Gap mine in Lancaster County, Pennsylvania. For their description the reader is referred to the easily accessible literature on Sudbury. Here it is only necessary to mention that at some of the many mines in the Sudbury district the quantity of nickel and copper in the sulphides is stated to be as follows:

Creighton (the largest deposits)	5.5	per cent. Ni	+ 2	per cent.	Cu
Crean Hill	3.1	per cent. Ni	+ 4.1	"	"
Garson	3.2	per cent. Ni	+ 4.2	"	"
Victoria	2.3	per cent. Ni	+ 4.	"	"
Worthington	4.	per cent. Ni	+ 4.6	"	"

The sulphides of most of the other mines carry from 3.5 to 4 per cent. of nickel.

According to the "Report of the Royal Ontario Nickel Commission," 1917 (p. 425), there had been smelted in the Sudbury district, up to the end of 1916, 10,322,515 short tons of ore, with a content of 284,838 tons of nickel and 175,003 tons of copper. The smelted ore averaged consequently 2.76 per cent. of nickel, which corresponds to about 4 per cent. of nickel in the sulphides as a whole. The ratio of the metals was 61 copper to 100 nickel.

The quantity of nickel in the sulphides as well as the proportion between nickel and copper is subject to great variations in the different deposits of the Sudbury district.

REVIEW.

The percentage of nickel in the total sulphides at the Norwegian deposits described, as well as at Alexo in Canada and Klefva in Sweden, is given below in a tabular summary.

*In Peridotites.**

	Approximate Nickel Content Per Cent.
Alexo	8
Bruvand	7
In Olivine-carrying Pyroxenite.	
Espedalen	4-5
In Norites and Hypersthenite-norites.	
Hosanger	6.5
Beiern	6.5–7
Flaad	4–4.5
Bamle	3.75–4
Romsaas	3.5–3.75
Skjækerdalen	3.5
Senjen	3.5
Erteli	2.5–2.75
Klefva	2.6
Sigdal	2.5

I know only two deposits of peridotite relatively poor in iron and rich in magnesia, Alexo and Bruvand, both of which are characterized by an exceptionally high percentage of nickel in the total sulphides—7 to 8 per cent. Both deposits are small.

* Serpentinized at Alexo.

The exceptionally high percentage of nickel in the sulphides from these two deposits must stand in relation to the fact that a peridotite rich in olivine, especially one with much MgO and relatively little FeO, is the primary igneous rock which on the whole carries the most nickel. Nevertheless, in spite of the high nickel content, which would be expected in the contained sulphides, I know of only the two deposits mentioned above, and these are very small. This is to be accounted for by the fact that the peridotites as a rule are almost entirely lacking in sulphides.

The deposits in Espedalen, in an olivine-bearing pyroxenite (with rather less MgO and somewhat more FeO than in the olivine of most peridotites), contain in the total sulphides about 4.5 per cent. of nickel, which is considerably less than in the two above-mentioned deposits in peridotite, but more than in the great majority of the deposits in norite.

Most of the best known deposits of nickel-pyrrhotite in norite, not only in Norway, but also at Sudbury, South Africa, and other places, contain from 3.5 to 4 per cent. of nickel in the sulphides. Some offset-deposits (with Vermilion, in the Sudbury district, as the typical example) contain still higher percentages of nickel and copper. These deposits, however, certainly represent a squeezing out of a sulphidic residual rich in nickel and copper, and not the original parent sulphide magma.

Within the larger Norwegian deposits the highest content of nickel in the total sulphides is about 6.5 per cent., namely at Hosanger. The rock is here a hypersthenite-norite (analysis No. 6) with about 20 per cent. of labradorite and not less than 80 per cent. of hypersthene, plus diallage, amphibole and some biotite. This rock thus contains a larger proportion of ferromagnesian silicates than any other nickeliferous norites in Norway. In conformity with this, we find a particularly high percentage of nickel, viz., 0.058, in the Hosanger norite itself with 0.126 per cent. of nickel in the hypersthenic segregations free from plagioclase and pyrrhotite.

A correspondingly high percentage of nickel, viz., 6.5 to 7 per cent. in the total sulphides, is found also in the inconsiderable

deposit at Beiern, where the uralitized rock seems to be derived from a hypersthenite-norite.

At the other extreme, among the larger or better known deposits, the lowest percentages of nickel in the total sulphides, viz., 2.5 to 2.75, are found at Erteli, in Norway, and Klefva, in Sweden, both of which are among the largest deposits in the Scandinavian peninsula. At both of these localities, the norite, in contrast with that of other fields, with the possible exception of Skjaekerdalen, is ophitic, showing that the labradorite began to crystallize at a very early stage. The norite at both places also carries a little quartz, only about 2 per cent., and contains relatively little hypersthene. Thus among the larger and best known deposits, the lowest percentage of nickel in the total sulphides is found in norites with relatively low content of hypersthene or other ferromagnesian silicates.

I shall now consider the deposits in which the sulphides have an intermediate content of nickel, between 3.5 and 4.5 per cent.

At Flaad, Evje, with from 4 to 4.5 per cent. of nickel in the sulphides, the rock in the vicinity of the mine is entirely uralitized, but was probably originally a norite fairly rich in hypersthene, with perhaps diallage. In Bamle, where the sulphides contain from 3.75 to 4 per cent. of nickel, the rock is a common norite with a slight excess of hypersthene above the labradorite-hypersthene eutectic limit. At Romsaas, where the sulphides contain from 3.5 to 3.75 per cent. of nickel, the rock is a hypersthene-rich norite, or hypersthenite-norite, which always carries some quartz; so that it is a relatively siliceous member of the norite group. In proportion to the high contents of hypersthene in the rock (not less than about 63 per cent.) the nickel content of the sulphides is rather low. At Skjaekerdalen occurs a relatively basic norite, with about 3.5 per cent. of nickel in the sulphides. The ore shows enrichment in labradorite as well as in sulphides, indicating that the noritic magma contained a slight excess of the labradorite molecule above the labradorite-hypersthene eutectic.

Thus for the larger noritic nickel deposits in Norway and Sweden it appears that the highest percentage of nickel (Ho-

sanger) is found in the norite richest in hypersthene, the lowest percentage of nickel (Erteli, Klefva) in the norite relatively poor in hypersthene (or hypersthene with diallage), and intermediate percentages of nickel in the rocks having an intermediate content in hypersthene. In other words, the percentage of nickel in the sulphides is dependent essentially on the content of hypersthene (or hypersthene plus diallage, primary amphibole, and biotite) in the rock. Other factors were probably operative, however.

Attention may be called to the fact that the percentage of nickel in the sulphides is higher in the segregations in the peridotites than in the segregations in the norites. This must be due to a higher general content of nickel in the peridotites than in the norites.

The following tabular summary brings out compactly the relation between the percentage of nickel in the noritic rock and in the segregated sulphides:

Locality.	Ni in the Rock Per Cent.	Ni in the Sulphides Per Cent.
Hosanger	0.058	6.5
Romsaas	0.042	3.5–3.75
Bamle	0.030	3.75–4
Erteli	0.023	2.5–2.75

Thus in the main with increasing percentage of nickel in the rock, there is an increasing percentage of nickel in the segregated sulphides, although there are some irregularities.

It may further be instructive to compare the percentage of MgO in the mother rock with the percentage of metallic nickel in the segregated sulphides, and from this to calculate the proportion by weight between MgO in the rock and Ni in the segregated sulphides. This is done in the following table:

For the 8 deposits for which we have fairly adequate material for this calculation, the proportion varies between 17 and 47 nickel to 100 MgO. If we also include the other Norwegian deposits, for which we know, at least approximately, the contents of the rock in magnesia, it appears as a general result that the amount of MgO in the mother rock and the amount of metallic

nickel in the segregated sulphides will fall between 15 and 50 nickel to 100 MgO.

Locality.	Mg in the Rock, Per Cent.	Ni in the Sulphides, Per Cent.	Parts, by Weight, of Ni in the Sulphides to 100 Parts of MgO in the Rock.
In peridotites:			
Bruvand	39.5	7	18
Alexo	35	8	22
In olivine-carrying pyroxenite:			
Espedalen	27	4.5	17
In norites:			
Hosanger	13.9	6.5	47
Bamle	10.9	3.75–4	35
Romsaas	15.8	3.5 –3.75	23
Erteli	9.1	2.5 –2.75	30
Klefva	8	2.6	32

The cause of this relation between the MgO of the rocks and the nickel of the sulphides—a relation subject to astonishingly small variation—must be that the nickel in the parent magma accompanied the magnesia in the differentiation of the magma, and that the percentage of nickel in the resulting partial magma was one of the main factors in the further concentration of nickel in the sulphides during their final magmatic segregation.

At several places deposits of the nickel-pyrrhotite type occur in gabbro, but they show so little nickel in the sulphides that they are not worth working. They have therefore not attracted much attention.

It cannot be an accidental circumstance that all but two of the nickel-pyrrhotite deposits, which have been worked economically, occur in norite. The two exceptions occur in peridotite, and olivine-pyroxenite, but not a single one is known in diallage gabbro. This must be connected with the fact that the norites are in the main richer in nickel than the diallagic gabbros.

I know of only two deposits of nickel-pyrrhotite in anorthosite, both very small and poor in nickel, viz., those at Ekersund and Soggendal in Norway. The percentage of nickel in the pyrrhotite from these occurrences is less than 1 per cent. In the geo-

logical literature are described two somewhat analogous deposits in syenitic rocks, but with very little or no nickel.

ON THE RELATION BETWEEN NICKEL AND COBALT.

From 8 analyses of pentlandite, the first seven from Sudbury and the last from Beiern in Norway, the ratio between nickel and cobalt in pentlandite has been calculated as 100 parts of Ni to respectively 2.6, 2.5, 2.4, 2.4, 2.3, 2.1, 2.0 and 1.4 parts of Co, thus, in most cases, 2 to 2.5 parts of Co. In this connection it must be remembered that a considerable proportion of cobalt, but very little nickel enters into the composition of pyrite, which crystallizes before the other sulphides. At Erteli, Flaad, and Bamle, the greater part of the cobalt of the sulphides is in this early pyrite. It is established that at least $^{9}/_{10}$, perhaps even $^{19}/_{20}$, of the total content of nickel in the sulphides enters in the pentlandite; but according to various investigations which I shall not cite here I consider it probable that a little nickel, very little, however, and also a little cobalt enter stoichiometrically as mixcrystal components in the pyrrhotite. The contents of cobalt in the sulphides is thus distributed between at least two minerals, pyrite and pentlandite, and a very little of it probably goes also to the pyrrhotite.

In the smelting the cobalt is much more likely to go into the slag than the nickel, and even during the smelting to the "first matte" some cobalt is lost. Thus in a matte from Sudbury which contains

Fe.	Cu.	Ni.	Co.	S.
About 42.....	14	17	0.5–0.6	About 25.

or 100 parts of Ni to about 3.3 parts of Co, it must be concluded that the contents of Co in the ore were considerably greater, probably 100 Ni to 5 or 6 Co.

Usually the ratio between nickel and cobalt in the sulphides of the nickel deposits appears to be 100 Ni to from 6 to 12 Co, or, on the average, 100 Ni to 8 Co.

COPPER IN THE NICKEL-PYRRHOTITE DEPOSITS.

By calculation from the percentage of nickel in the sulphides and the ratio between nickel and copper is obtained the following summary:

Locality.	Ni Per Cent	Cu Per Cent
Deposits in Peridotite.		
Bruvand	7	1.5
Alexo	8	1.5
Deposits in Olivine-carrying Pyroxenite.		
Espedalen	4.5	2
Deposits in Norite and Hypersthenite-norite.		
Hosanger	6.5	2.2
Flaad	4–4.5	2.75
Bamle	3.75–4	1.75
Romsaas	3.5–3.75	1.5
Senjen	3.5	1.4
Erteli	2.5–2.75	1.9
Klefva	2.6	1.4
Graagalten	2.5	1.5

The percentage of copper in the sulphides as a whole, when special offset-deposits are not taken into consideration, is subject to relatively small variations. It is particularly noticeable that the percentage of copper does not increase proportionally with the percentage of nickel.

CONCLUSIONS.

The tenor of nickel in the deposits of nickel-pyrrhotite is undoubtedly determined by more than one factor. It appears, however, that one of the most important factors is the amount of nickel originally present in the ferromagnesian silicates of the rock. This nickel content is generally higher in the peridotites than in the norites and higher in the norites than in the diallagic gabbros. In the norites, the percentage of nickel increases in the main with the amount of hypersthene present. Among the

other factors operative is probably the quantity of sulphide segregated operative per unit weight of the silicate magma.

As I have shown in earlier treatises the transference of nickel from the magmatic silicate compound to the sulphid compound must be due to a chemical reaction, illustrated by the following scheme:

FeS + Ni-cation in silicate-compound $\rightleftarrows$ NiS + Fe-cation in silicate-compound.

The smaller the quantity of RS, mainly FeS, which is present, the more nickel must this absorb under otherwise identical conditions, *i.e.*, in very small sulphidic segregations we may expect a relatively high percentage of nickel.

What is true of nickel will also be true of cobalt. The proportion between nickel and cobalt in the sulphides will thus almost exactly represent the proportion between the two elements in the original magma.[52]

During magmatic segregation some copper always goes into the sulphides, even in the peridotite-magmas which must thus contain also a little, though only a very little, copper. Attention is directed to the fact that the percentage of copper in the total sulphides is subject to relatively small variations only, and does not increase with the percentage of nickel.

On account of the predominant tendency of the copper to enter into sulphidic compounds, we must conclude that the original content of copper in the magma has been much more strongly concentrated in the sulphides than the nickel and cobalt. The proportion between nickel and copper in the sulphides, an average of 100 parts by weight of nickel to 60 parts by weight of copper, thus does not indicate a similar proportion between the two metals in the silicate magma, but only determines the maximum pro-

[52] See my paper in *Zeit. f. prakt. Geol.*, 1898, p. 237. Here is tabulated the proportion between nickel and cobalt in 74 analyses of meteoritic and terrestrial iron. More than two thirds of these analyses lie between 1 Co: 8 Ni and 1 Co: 20 Ni, and a large number of the analyses are grouped around 1 Co: 10–15 Ni with a mean of 1 Co: 12 Ni. Without recalling this old work I have estimated the proportion between the two metals in the sulphidic ores to average 100 Ni: 8 Co, or 1 Co: 12.5 Ni.

portion of copper originally present in the magma. If we take the average percentage of nickel in the norites as 0.030 and in all of the igneous rocks as 0.010, the norites should contain less than 0.018 per cent. of copper and igneous rocks as a whole less than 0.006 per cent. of copper. Probably these numbers are considerably too high.

TRONDHJEM,
NORWAY.

THE PETROLEUM POSSIBILITIES OF COSTA RICA.

ARTHUR H. REDFIELD.[1]

INTRODUCTION.

A zone of folded Tertiary sedimentary rocks in the Sixaola and Estrella valleys of southeastern Costa Rica is most definitely indicated by a review of the geologic evidence at hand as one likely to contain oil. The northward continuation of this zone is not disclosed from the data at hand, but it seems possible that it may extend almost to San Juan River. North of the Costa Rican Railway, the structure is hidden under a thick cover of volcanic tuff and agglomerate from Mt. Turrialba. On the Pacific side of Costa Rica still less is known of such a belt from published accounts, but the evidence at hand would suggest the advisability of prospecting the coastal ranges and foothills from the Panaman border to the Gulf of Nicoya.

SOURCE OF DATA.

Published accounts of geologic exploration of Costa Rica deal almost entirely with traverses along three principal routes: (1) Across the narrow neck of land separating Lake Nicaragua from the Pacific Ocean, along the south shore of Lake Nicaragua, and down San Juan River to the Caribbean Sea; (2) along the railroad route from Puntarenas to Puerto Limón via San José; and (3) from the mouth of Diquís River across the Térraba valley over the Cordillera de Talamanca and down Sixaola River to its mouth. The first of these traverses was surveyed by C. W. Hayes in 1898 for the Nicaragua Canal Commission. Alfaro. Along the third route the researches of Pittier in the In central Costa Rica, geologic studies along the railroad route have been made by Attwood, Gabb, Hill, Sapper, Romanes, and

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Térraba valley and of Gabb and MacDonald, in the Sixaola valley, constitute the principal basis of our information.

In general the geologic information available on Costa Rica lacks coördination. The geologic studies of Central America made by Sapper come nearest to filling this need; but these are limited by the lack of paleontologic evidence which has more recently become available. Valuable work has been done by Vaughan and his associates, and by Berry, notably in the U. S. National Museum Bulletin No. 103, and in the Proceedings of the First Pan-Pacific Scientific Conference, in correlating the sedimentary formations of Central America and the West Indies with those of the United States. The Sinclair Consolidated Oil Corporation has released valuable data in the recent writings of MacDonald and Olsson.

In the preparation of the present literature study valuable counsel, criticism, and data were furnished by Messrs. T. Wayland Vaughan, W. P. Woodring, and J. D. Sears, of the U. S. Geological Survey, to whom the writer takes this opportunity to express his indebtedness.

SURFACE FEATURES.

Though Costa Rica is one of the least mountainous of the Central American States, important mountain systems traverse the middle of the Isthmus from one end of the Republic to the other, dividing Costa Rica longitudinally into three physiographic provinces: (1) the Caribbean plain, (2) the middle cordillera, and (3) the Pacific coast ranges and valleys.

The triangular Caribbean plain which occupies nearly one-third of Costa Rica extends from Lake Nicaragua and San Juan River to the Panaman frontier. It may be subdivided into two parts: (*a*) the Plain of San Juan which extends from Lake Nicaragua and San Juan River to Limoncito River south of Puerto Limón; and (*b*) the Talamanca Plain, which extends from Limoncito River to Almirante Bay, in Panama. The San Juan Plain is extremely level, its even surface being broken only in the northeast by the Cerros de San Carlos (about 330 feet in altitude),

the Cerro de Colorado (430 feet) and the Cerro de Lomas (1,160 feet). The Talamanca Plain consists of a coastal zone of low and swampy lands and an interior zone of rolling foothills, cut by the broad flat valleys of Sixaola and Estrella rivers.

The central cordillera is divided by the valleys of Rio Grande and Rio Reventazón into two distinct ranges. The northern range consists principally of a number of volcanic peaks that increase progressively in height from Orosi (5,154 feet) in the northwest to Irazú (11,325 feet) and Turrialba (10,955 feet) in the southeast. The "Volcanic Range" is somewhat curved, so that the summit-line describes a great arc, of which the concave side lies toward the Caribbean Sea and the convex side toward the Pacific Ocean. It extends from 10° to 11° N. in a general NNW.–SSE. direction, between 83° 30′ and 85° 30′ of longitude west of Greenwich.

The southern range, generally known as the Cordillera de Talamanca, is more extensive than the northern range and considerably higher. Its greatest elevation probably exceeds 3,800 meters (12,470 feet). The Cordillera de Talamanca begins south of San José with the volcanic peak of Iscazú (6,370 feet) and culminates in the unexplored group of Chirripó Grande (about 12,470 feet); from there the range decreases in height to the southeast, ending in the Cerro Pando, which does not greatly exceed 2,000 meters (6,560 feet) in altitude. From the main cordillera several rugged spurs extend to the east.

In the Pacific physiographic province the surface is more complicated. The Cordillera de Talamanca is paralleled on the southwest by a Pacific coastal range which begins at Savegre River and ends abruptly at Rio Chiriquí Viejo in Panama. The Pacific coastal range is separated from the Cordillera de Talamanca by intermontane valleys of which the Térraba Valley in the basin of Diquís River is chief. Connected with the mainland by low alluvial plains are the three large rugged peninsulas, Nicoya, Osa, and Burica.

GENERAL GEOLOGY.

The geology of Costa Rica is reflected in its surface features. The Caribbean plain is composed of but slightly consolidated sedimentary rocks of Tertiary and Quaternary age. The middle cordillerra is of igneous origin, consisting in the southeast of pre-Tertiary intrusives and in the northwest of Teritary and later effusives. The Pacific coastal ranges and peninsulas consist chiefly of folded Cretaceous (?) and Tertiary sedimentary rocks or of late effusives and plutonic rocks of unkown age.

The Caribbean plain of Costa Rica is largely underlain by a zone of Tertiary sedimentary rocks which extend with apparent interruptions and in varying breadth from Lake Nicaragua and San Juan River to the Panaman border. These rocks are not only closely folded and considerably faulted near their contact with the middle cordillera, but are intruded to a considerable extent on their inner margin by igneous rocks of various ages. A second zone of igneous intrusion occurs in the hills (*cerros*) of the middle and lower parts of the San Juan Valley, apparently a continuation of the principal cordillera of Nicaragua. Quaternary sediments occur on the beaches and in the raised coral reefs which fringe the shore, and form the surface of much of the Caribbean plain.

The broad mountainous zone which forms the backbone of the Isthmus is composed almost entirely of igneous rocks. This zone extends at places to the Atlantic and Pacific shores. It includes the Cordillera de Guanacaste, the Cordillera Central, and the Cordillera de Talamanca, with their numerous offshoots. The Cordillera de Guanacaste and the Cordillera Central consist of a number of dormant or slightly active volcanoes, and of the volcanic rocks derived from these. Beneath these relatively late volcanic deposits a core of earlier plutonic rocks is believed to occur. The central valley, which separates the "Volcanic Range" from the Cordillera de Talamanca, is covered by a sheet of volcanic ash, intruded by dikes and by stratified rocks many of which are apparently sub-aqueous depositions of volcanic ash. The Cordillera de Talamanca is made up the large part of plu-

tonic rocks cut in many places by later intrusions and overlain in other places by flows of later effusives.

In the Pacific province the coastal hills which border the bays of Salinas and Santa Elena are composed of Lower Tertiary sedimentary rocks. Folded Lower Tertiary sedimentary rocks and Cretaceous (?) limestones form the coastal ranges and foothills which border the Pacific coast of Costa Rica from the Gul of Nicoya to Mala Bay and continue beyond Rio Diquís to the Panaman frontier. The Osa and Burica peninsulas appear to be outliers of Tertiary sedimentary rocks.

Intrusives and extrusives of unknown age form the central mass of the Nicoya Peninsula. The older igneous rocks are overlain unconformably by Cretaceous (?) and Tertiary sedimentary rocks, which are considerably altered by contact with the later intrusions.

The Nicoya and Osa peninsulas are connected with the mainland by Quaternary alluvium. Extensive deposits of alluvium fill the valleys of Rio Grande de Tárcoles, Rio Pirrís, and Rio Coto.

STRATIGRAPHY.

Sedimentary Rocks.

Cretaceous (?) or Eocene.—The oldest known sedimentary rocks in Costa Rica consist of sandstone and marl, occurring near Desamparados, and the so-called San Miguel limestone. The irregular jointing of the sandstone and marl beds, together with a certain amount of staining by infiltration, has almost entirely obliterated the bedding, and has made it difficult to determine their exact relation to the limestone. Romanes (35) considers it more probable that they underlie than overlie the San Miguel formation, and this view is shared by Alfaro. (3)

The formation exposed near Desamparados varies from a loose, friable, pale-yellow sandstone locally stained bright red to a very fine grained, pale-yellow marl. As exposed at El Higuito to a few miles west of San Miguel, the sandstone is formed of angular fragments of quartz; with the quartz grains

are fragments of feldspar and devitrified volcanic glass. The cement is red oxide of iron. The rock, which contains marine fossils, suggests by its composition that deposition was rapid, and that explosive volcanic action had a part in the preparation of the material. The marl, deep yellow in color, is well exposed at Tres Rios. A thin bed of carbonaceous shale occurs locally interstratified with the sandstone. At one place, about seven miles south of San José, where the carbonaceous material is about nine feet thick, there is some low-grade coal. In 1922, however, two Americans were reported to be mining a coal of fair grade at El Tablazo, and selling it in San José.

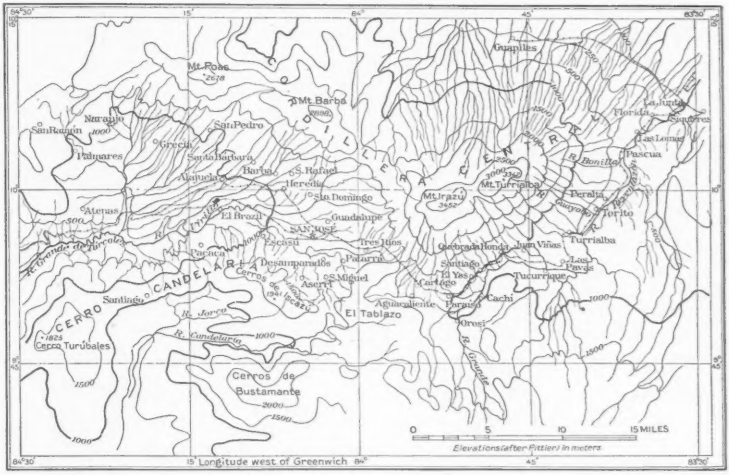


FIG. 59. Central Costa Rica.

The age of the Desamparados formation has not been determined. Sapper (39) notes the occurrence of a specimen of *Pecten* in the sandstone member. According to Romanes, (35) numerous well-preserved specimens of the genus *Pecten*, apparently closely allied to a smaller type found in the San Miguel limestone, occur in the yellow marl at El Brazil, and fragmentary and poorly preserved specimens of the genera *Pectunculus, Astarte, Arca,* and *Pyrula,* near Patarrá.

The San Miguel limestone varies considerably in lithologic character, according to the amount of weathering it has undergone. The least altered type is a hard, compact bluish-gray or blue-black, impure limestone, largely composed of fragmental organic remains. The impurities consist of angular fragments of quartz and a few small crystals of plagioclase, together with numerous small fragments of yellow volcanic glass, some of which are devitrified. The limestone when exposed in the quarry at Patarrá is greatly jointed, with slickensliding on the joint planes and considerable mineral recrystallization. The upper part of the limestone for a depth of eight or ten feet is weathered into a loose clay interspersed with scattered fragments of weathered limestone. The limestone at the Tres Rios quarries is similar in lithologic character to that of Patarrá. Here the leaching out of the calcareous matter leaves a loose sandstone-like material, that could not be recognized as the residue of a limestone, were not the results of the various stages of the process visible. At Aguacaliente, 2 miles south of Cartago, the limestone has been almost completely recrystallized by the hot springs to which the places owes its name.

Hill (20) considered the San Miguel limestone to be Cretaceous on the basis of the presence of remains of supposed *Inoceramus* and *Rudistes*. Romanes (35), however, identified the supposed *Inoceramus* remains as *Pecten*, and from the occurrence of numerous *Balani* considered the San Miguel limestone to be Tertiary. Certain badly preserved foraminifera were supposed by Romanes to represent orbitoidal foraminifera.

Some light may be shed on the age of the San Miguel limestone by the occurrence of a calcareous formation in the Nicoya basin, which presents strong analogies. On Abangares River on the east side of the Gulf of Nicoya is the cream-colored Colorado limestone described by MacDonald (25) and by Romanes (35), which resembles lithologically the San Miguel limestone in that it contains some feldspar and fragments of cryptocrystalline silica. The Colorado limestone contains numerous organic remains, especially foraminifera, belonging to *Rotalia* and allied genera,

together with some poorly preserved corals and calcareous algæ of the nature of *Nullipores*. It has furnished by its erosion part of the material of the Manzanilla breccia which is lower Oligocene or upper Eocene, according to Vaughan (47); and on the Nicoya Peninsula fragments of the limestone and chert series are contained in the Nicoya Ashy Series which Romanes (36) regards as the equivalents of the Manzanilla formation. The Colorado limestone of the Nicoya basin, and by inference the San Miguel limestone, would appear accordingly to be older than Oligocene and younger than Cretaceous.

The Brito beds (Eocene)[2] of southwestern Nicaragua are reported by Hayes (19) to extend along the south shore of Lake Nicaragua in the foothills of the north slope of the Cordillera de Guanacaste. The exposures on the headlands of the lake shore consist almost entirely of resistant blue calcareous sandstone apparently containing a high proportion of volcanic ash, and coarse volcanic breccia similar to those occurring at various points along the Pacific coast of Nicaragua. A series of well-bedded sandstone, conglomerate, shale, and volcanic debris, apparently a continuation of the Brito formation of Nicaragua was found by Pittier (31) on the shores of the bays of Salinas and Santa Elena, and similar rocks occur in the Pacific coastal range between Naranjo and Savegre rivers.

The geologic equivalent of the Brito beds in the valley of San Juan River, according to Hayes (19), is the Machuca formation which consists chiefly of calcareous shale with interbedded subordinate sandstone. The constituents of the sandstone are largely igneous in their origin. No pure limestone or distinctly marly beds have been discovered in the San Juan valley.

Oligocene.—The Oligocene of the Caribbean slope of Costa Rica consists, according to Olsson (28), of sandstone, shale, and a complex of hard, and in many places, semi-crystalline lime-

[2] According to Vaughan (Bull. U. S. Nat. Mus. No. 103, p. 591, Washington, 1919), Hayes included in the Brito formation, which he considered Oligocene, beds ranging in age from the upper Eocene to the lower Miocene, successively higher beds being exposed toward the northwest. At the type locality the Brito beds are upper Eocene.

stone which pass through all gradations to coarse arkosic sandstone. The most abundant and characteristic fossils are the orbitoidal foraminifera of the genus *Lepidocyclina*. The age of these beds probably ranges from lower to upper Oligocene.

The "limestone series" of the Caribbean slope described by MacDonald (22) is regarded by him as Oligocene, but some of the beds resemble the Eocene (?) of the Central Valley and the Nicoya Basin. The series consists of 500 feet of well-bedded pure crystalline limestone of a pinkish color. Some of the limestone beds contain granules and crystals of eruptive material. The upper beds are more clayey, and pass by transiton into the overlying Uscari shale. The "limestone series" is exposed in a zone extending from the upper waters of Coén River (tributary to Estrella River) to Chirripó River. It is apparently not exposed in the basins of Sixaola and Changuinola rivers. The beds are bent into irregular folds, much contorted, and intruded by igneous dikes.

In central Costa Rica, the lower Oligocene is represented by the Guallava (or Guayabo) formation which consists of a lower member of loose sandstone and fine-grained conglomerate, with intercalated marl. The lower member of the Guallava formation is overlain by the hard white compact Las Animas limestone, and by nummulitic limestone. Fossils found by Sjögren,[3] in the lower sandstone, were identified by Dall as belonging to the Vicksburg stage of the lower Oligocene. Cushman[4] substantiates this reference, on the basis of the presence of *Lepidocyclina hilli*.

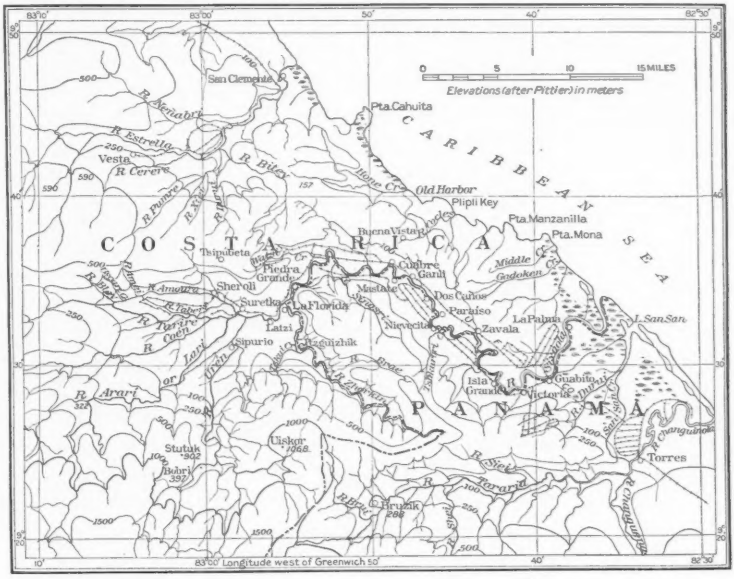
Romanes (35) gives the name of "Manzanilla beds" to a series of well-bedded ashy sedimentary rocks, which rest unconformably upon limestone apparently corresponding to the San Miguel beds and occupy the coastal plain east of the Gulf of Nicoya in the vicinity of Abangares River. On the Peninsula of Nicoya, Romanes' "Nicoya series" of marine volcanic ash and sedimentary

[3] *Bull. Mus. Comp. Zoöl. Harvard Coll.*, vol. 28, no. 5 (Geol. Series, vol. 3), p. 232, 275, Cambridge, June, 1898.

[4] U. S. Geol. Surv. Prof. Paper 125-*D*, p. 60, pl. 15, fig. 1; pl. 16, fig. 2, Washington, 1920.

rocks is held by that author (36) to correspond to the Manzanilla series of the mainland. On the basis of foraminifera identified by Cushman, Vaughan (47) assigns the Manzanilla beds to the lower Oligocene, or upper Eocene.

Miocene.—In Talamanca the oldest Tertiary sedimentary rock resting directly upon the syenite of the Sierra de Talamanca is the Uscari shale. Along the contact with the syenite the shale has been metamorphosed to slate. The unaltered shale which occurs to the northeast of Dipuk is soft, brown to black in color, and contains fossils. Its fauna consists largely of the smaller types of foraminifera, indicating that it was deposited in quiet and moderately deep water. Thin beds of sandstone near the top of the formation and a few limestones and calcareous sandstones are intercalated with the shale. The Uscari formation totals 2,000 feet in thickness. The indistinct bedding makes the structure hard to determine. In general the beds are closely


0 5 10 15 MILES
Elevations (after Pittier) in meters
C A R I B B E A N S E A
C O S T A R I C A
P A N A M A
San Clemente
Pta. Cahuita
Old Harbor
Pipli Key
Pta. Manzanilla
Pta. Mona
Vesta
R. Cerere
R. Bilin
R. Estrella
R. Sixaola
Bocas del Toro
Bocas Cr's
Bocas Cr.
Bocas Inlet
Bocas Island
Bocas Harbor
Bocas Entrance
Bocas Channel
Bocas Bay
Bocas Point
Bocas Mouth

folded showing dips of 20° to 90°, and in many places they are strongly faulted.

Gabb (12), following the older terminology, considered the Uscari shale to be Miocene. Hill (20), following a later usage, refered it to the Oligocene. MacDonald (25) also considered it Oligocene from its resemblance to the Cucaracha and Culebra formations of the Canal Zone. From the fauna it contains, Olsson (28) ascribes it to the lower Miocene.

A fauna described by Gabb (17) from Sapote on Reventazón River was considered by Olsson (28) to be contemporaneous with the Uscari fauna. The formation in which the fossils occurred consists of massive sandstone, brown and yellow shale, and some impure yellow limestone.

The Uscari shale is overlain, in marked unconformity, by sedimentary rocks belonging to the Gatun stage (middle and upper Miocene). The Gatun of Costa Rica is very much thicker than that of the Canal Zone, and represents paleontologically a longer depositional period. In fact, the typical Gatun of the Canal Zone represents, according to Olsson (28) only the lower part of the formation as developed in Costa Rica.

Lithologically, the Gatun formation of Costa Rica is characterized by marked lateral variation. Two principal phases occur: (1) the typical Gatun, in which the beds are chiefly sandy with some lignitic and coarsely conglomeratic beds, containing a near-shore fauna, and (2) the off-shore phase in which coralliferous limestone and richly fossiliferous marl predominate and lignite beds are absent. The near-shore phase prevails along the inner margin of the present Miocene zone; whereas the other phase is more common along the present coastal areas.

The inshore phase of the Gatun formation is exemplified by sandstone and shale exposed on Sheroli (or Xirores) Creek. Its principal member is a massive to distinctly-bedded, dark-gray to dark-bluish argillite. The rocks of the Sheroli formation are for the most part clayey and fine-grained, but they contain both marly beds and thin conglomeratic layers with rounded fragments of basic igneous rocks, and rounded coral fragments. Locally,

lenses and thin seams of lignitic shale and lignite occur. The dark colored argillite of the Sheroli formation crops out on Watsi (Uatsi or Guatsi) Creek and inside the coral reefs which form Mona Point. In the upper parts of the Sheroli formation are beds of fine-grained gray to cream-colored indurated clay similar to fuller's earth. Calcareous nodules or concretions characterize the formation. The upper part of the Sheroli formation, especially as exposed between Buena Vista and Cuabre, contain more sandstone than the lower part. The Sheroli formation is part of the Gatun formation of Costa Rica, as this term is used by Olsson (28). A flora collected by Woodring from beds that probably belong to the Sheroli formation was considered by Berry (7) to be younger rather than older Miocene.

In central Costa Rica, sedimentary rocks exposed at Bonilla Cliff on the railroad from Puerto Limón to San José were considered by Hill (20) to represent the Monkey Hill beds (Gatun formation, Miocene) of the Canal Zone. The Bonilla formation consists of yellowish sandstone, some of which is coarse and calcareous in composition and grades into marl. Boulders of a yellow fossiliferous marly sandstone occur on the banks of Bonilla River. Greensand marl occurring along the Puerto Limón-San José Railroad where it crosses Pascua River was correlated by Hill (20) with the Mindi beds (Gatun formation) of Panama.

Near Puerto Limón are a few hills standing about 40 feet above the surrounding coastal swamp. They are composed of greatly cross-bedded unconsolidated clay and sand. Gabb (17) described Pliocene fossils from these hills; according to Vaughan (47) and Olsson (28), as well as to earlier writers, they contain beds of both Miocene and Pliocene age. The hills are believed to be "monadnocks," or remnants of a higher physiographic surface whcih has been largely destroyed by erosion.

Miocene fossils of the Gatun stage have been recognized by Romanes (35) and by Alfaro (1) in the Barranca sedimentary rocks of the east coast of the Gulf of Nicoya, southeast of Puntarenas. These sedimentary rocks consist of various types of

volcanic material of different textures and composition, with a calcareous cement.

Pliocene.—The Pliocene of the Caribbean coast includes, according to Olsson (28), a certain reef limestone composed of coral and hydrozoa remains; also marl, blue lignitiferous clay, blue coarse sandstone, and a predominating hard conglomerate composed of large boulders of igneous rocks (the so-called "boulder clay" of several writers on Costa Rican geology).

The Gatun formation of Talamanca is overlain unconformably by the Suretka conglomerate, which is composed of thick beds of pebbles, cobbles, and even large boulders of andesite and basalt and of pebbles of quartz-diorite, cemented by silica. A few beds and lenses of argillite and sandstone are intercalated in the conglomerate. Locally, thin lenses of lignitic shale and brownish fragments of organic remains occur. No distinctive fossils have been found in this formation. MacDonald (22) at first considered it to be the age-equivalent of the Bohio conglomerate (Lower to Middle Oligocene according to Vaughan) of the Canal Zone, but in a more recent paper (25) considered it to be late Miocene or younger, perhaps in part Pliocene. Woodring,[5] however, considers the Suretka conglomerate to be probably of Pliocene age.

Particular interest has attached to the "boulder clay" of central Costa Rica which occurs, in many places to a considerable depth, on both the Caribbean and the Pacific slopes of the mountains. Belt,[6] from its similarity to the Boulder Clay of Great Britain, considered it to be of glacial origin. Hill (20) ascribed it to the rolling of material down the steep slopes of volcanoes into the valleys. Romanes (35) considers it to be due principally to rapid tropical weathering and torrential deposition, with talus deposition, and spheroidal weathering with subsequent rearrangement by percolating water as contributing causes. According to Olsson (24), the "boulder clay" interfingers with beds containing Pliocene fossils.

[5] Oral communication.

[6] Belt, Thomas, "A Naturalist in Nicaragua," pp. 259–264, London, 1874.

The projecting headlands of the Caribbean coast, notably Cahuita Point, Buridikur Point, Manzanillo Point, Mona Point, are formed of the impure "Caribbean" limestone, which is locally a coquina, and which contains in places coarse brownish beach sand as well as fragments of coral and shells. This limestone appears to have been originally a fringing reef. Similar coralliferous limestones near Puerto Limón contain Pliocene fossils. They may probably be correlated with the Toro limestone (Pliocene) of the Canal Zone. Similar reef limestones however, characterize the off-shore phase of the Gatun. The process of uplift which formed these Miocene and Pliocene coralliferous limestone reefs has continued apparently into the Recent period.

Quaternary.—The Quaternary alluvium of the San Juan valley consists chiefly of unconsolidated clay and sand. In the upper portion of the valley it consists of fine blue clay interbedded with fine blue and brown sand. In the lower portion of the valley the alluvium contains considerable black sand near the river and fine blue silt away from the river. The delta deposits at the mouth of Rio San Juan are similar to those of its lower flood plain.

In the central valleys of Costa Rica the Quaternary deposits consist chiefly of river sand and gravel, coarse conglomerate, tuff, volcanic ash, and boulder clay. On the Caribbean plain the Quaternary consists of finer-grained alluvium, chiefly unconsolidated sand and clay.

In Talamanca the Quaternary deposits consists of the gravel of the Buena Vista divide, the black mud and silt of the swamps and stream debris of the lower part of the Sixaola Valley, and the present sea beaches, bars, reefs, and alluvium.

Igneous Rocks.

A long narrow mass of granitic and syenitic[7] rocks forms the crest of the Cordillera de Talamanca. True granite is comparatively rare; syenitic rocks are much more common. The trend of these rocks is not coincident or coextensive with the mountain

[7] According to Vaughan (oral communication) the "granites" are generally quartz-diorites and the "syenites" are generally diorites.

range; they bear more to the east, Pico Blanco (Mt. Kamuk) being their culminating point. Monzonite constitutes the core of the Cerro Candelaria Range. From the presence at Siquirres of a granite boulder apparently washed from the Caribbean slope of the Turrialba range and from the occurrence of granite debris in Lower Tertiary sedimentary rocks near Siquirres, Hill (20) assumes the existence of a pre-Tertiary plutonic core beneath the late eruptive flows of the Volcanic Range of northern Costa Rica. Diorites occur in the core of the Nicoya Peninsula, and also in the Cordillera de Talamanca. Diorite boulders were found by Sapper (35) at El Sardinal, Province of Guanacaste, and at San Pablo, Province of San José. Quartz-diorite boulders were found by Sapper (35) at Cariñac, near Tambor, Province of Cartago.

Dikes of porphyritic rocks are common in all of the regions of great and even moderate disturbance. They are intruded in both the Tertiary sedimentary rocks and in the plutonic rocks which form the core of the sierra. The granite and syenite of the Cordillera de Talamanca are extensively intruded by porphyritic dikes. The monzonite of the Cerro Candelaria range is intruded by olivine diabase.

Among the late eruptive rocks occurring in Costa Rica Hill (20) mentions melaphyre, enstatite-porphyrite, and mica-diorite-porphyrite. Phonolite was reported by Seebach (41) from Culebra Bay. Andesite, especially augite-andesite, is widespread in its occurrence. Flows of pyroxene-andesite occur in the Cerro Candelaria Range. Diabase is abundant in the Nicoya Peninsula. Basalt likewise occurs throughout a wide area. Trachyte, dacite and rhyolite are known in Costa Rica only in a few isolated outcrops.

TECTONICS.

General Statement.

The mountain systems of Costa Rica and Panama represent tectonic arcs generally parallel to those of Guatemala and Honduras, but independent of them in structure. The axial mountains of southern Central America were formed, according to

Sapper (38), later than those of northern Central America, and from different orogenic centers.

The mountains of Central America are divided by Sapper (38) into two systems, a northern or "Guatemalan" system, to which the mountains of Guatemala, Honduras, and northern Nicaragua belong, and a southern or "Costa Rican" system, which includes the mountains of Costa Rica and Panama. These two systems resemble one another in their general direction, which is that of an east-and-west arc convex to the south; but differ in their centers and radii of curvature. The intersection of the two arcs is masked by the tuff sheets and lava flows of central Nicaragua.

The southern or "Costa Rican" system begins on the Isthmus of Panama and dies out in the isthmus between Lake Nicaragua and the Pacific. Although at first glance the mountain system of Costa Rica and Panama appears to form a single mountain arc with several parallel ranges, on closer study, however, it is recognized that here are two arcs of similar curvature, whose ends are separated in the upland of Costa Rica by an interval of about 16 miles. The one arc consists of the main range of the Cordillera de Talamanca; the other of the Pacific coastal ranges.

These parallel mountain arcs are separated in central Costa Rica by the Iscazú-Turúbales range or Cerro Candelaria which extends east and west, and is paralleled by a second range to the south. The researches of Romanes (35) show that the Cerro Candelaria contains a core of plutonic rocks, cut by later intrusives and overlain by late igneous flows and by Tertiary sedimentary rocks. Sapper (38) suggests that the presence of the Cerro Candelaria range, which he presumes to be older than the present Cordilleras, may have caused the division of the "Costa Rican" system into a North Costa Rican arc and a Costa Rican-Panaman arc.

Sapper (38) postulates three principal periods of diastrophism in Central America, (1) at the close of the pre-Cambrian; (2) at the close of the Paleozoic; and (3) late in or at the close of

the Miocene. To these Powers[8] adds a fourth, late in or after the Pliocene.

It is uncertain what part was played by Paleozoic or older movements in the development of southern Central America. Hill (20) postulates the presence of a pre-Tertiary basement barrier of granitic rocks, trending east and west, which furnished by its erosion the materials from which the Tertiary sediments were formed. According to Vaughan (45, 47, 48), the principal tectonic lines of the perimeters of the Gulf of Mexico and Caribbean Sea existed at the close of the Paleozoic. Accordingly land conditions appear to have existed in Costa Rica throughout the Triassic and Jurassic periods, and probably even throughout the Cretaceous if Romanes' identification of the fossils in the San Miguel limestone is correct.

The first extensive submergence of Costa Rican territory in Tertiary time appears to have begun in the Eocene. This continued through the Oligocene into Lower Miocene time, when the Caribbean slope and the Central Valley of Costa Rica shared in the widespread depression which is indicated by the extensive occurrence of Miocene beds around the Gulf of Mexico and the Caribbean Sea. The Pacific Slope likewise appears to have shared in the submergence. The Caribbean Sea and the Pacific Ocean were connected by a strait through central Costa Rica.

The Uscari-Gatun unconformity is evidence of diastrophic movements which resulted in a brief withdrawal of the Miocene sea. The central land mass was apparently elevated to greater height, as is shown by the occurrence of coarser materials in the Gatun formation than in the Uscari shale. The interoceanic connection was narrowed and possibly even closed for a time. The Gatun stage was marked by renewed submergence, a greater transgression of the sea on both coasts, and a reopening of the interoceanic strait.

The Pliocene in Costa Rica was a period of local submergence along the coast, of high elevation in the interior, of intense fault-

[8] Powers, Sidney, notes on the geology of eastern Guatemala and northwest Spanish Honduras: Journal of Geology, vol. 26, No. 6, p. 523, Chicago, 1918.

ing, and of intense volcanic activity. The coarse Suretka conglomerate and the much discussed "boulder clays" were formed by the erosion of these Pliocene lava flows and the redeposition of the eroded material. The Quaternary was marked by volcanic activity in the west, and by sedimentation in the lagoons of both coasts.

Folding.

On the Caribbean side of the Isthmus, tectonic forces exerted along a line normal to the present mountain structure of the isthmus, have resulted in the formation of anticlines and synclines trending generally parallel to the main axis of the isthmus. In the districts nearest to the central cordillera the strata are steeply-dipping, closely folded, highly shattered and faulted, with numerous dikes and igneous intrusions. The folding is less intense near the Caribbean coast.

The sedimentary rocks of the Brito formation exposed on the northeast slope of the Cordillera de Guanacaste were considered by Hayes (19) to form the eastern limb of a broad anticline, whose axis extends northwest-southeast in the narrow isthmus between Lake Nicaragua and the Pacific Ocean. The Brito beds exposed on the shore of Lake Nicaragua dip 5° to 30° NE.

In the Machuca formation of San Juan River, Hayes (19) noted the presence of a syncline between Caño Bartola and Machuca, and of numerous sharp folds at Machuca. The axes of these folds trend generally northwest-southeast. Although in general the dips are low, the formation has undergone considerable local dislocation. Breccias, probably due to faulting, have been observed at several points, notably at the mouth of Rio Machuca. Numerous dikes intersect the sedimentary rocks. The exposures of the Machuca formation are not sufficiently numerous to render the details of its structure determinable.

Along the Costa Rica Railway from Puerto Limón to San José the structure is complicated, especially in the central valleys. The occurrence of marine Miocene beds in the interior of Costa Rica at altitudes of several thousand feet gives evidence that in

Miocene time an east-west trending geosyncline connected the Atlantic and Pacific Oceans. This major structure is apparently complicated, however, by cross-folding, faulting, and igneous intrusion.

.The structure of the Department of Limón between Puerto Limón and Old Harbor (Puerto Viejo) is known almost entirely from the reconnaissances of Sapper (39). The lignite-bearing Miocene sandstone exposed along Rio Banana strikes N. 75° to 85° W., and dips 15° to 40° N. Sapper's observations along Estrella River and its upper tributaries show a complicated structure near the mountains, and strikes toward the coast generally parallel to the main trend of the isthmus.

In Talamanca, the structure is complicated. In general the strata are folded into anticlines and synclines trending N. 55° to 60° W. Igneous intrusions occur in the vicinity of Piedra Grande, and in the divide between Sixaola and Estrella rivers above Sheroli (39). At the mouth of Urén River, according to Sapper (39), the Suretka conglomerate dips north-northwestward, a little farther downstream eastward, still farther downstream westward; and at Latzi (Bratzi) gently westward. Gabb (12, 16), notes the presence below the mouth of Urén River, of broad folds, of which the major axes bear generally NW.–SE. East of the igneous intrusion at Piedra Grande, according to Sapper (39), the sedimentary formations dip gently westward. At Punta Yarban the Gatun formations dip gently southeast; at Sibube (Sibouwe) the dip is 80° S., and at Cuabre 35° SW.

Close folding is indicated by Gabb (12,16) in the Zhorkin basin. On Izgui (or Tskui) Creek, a couple of miles above its junction with the Zhorkin, a conglomerate of the Gatun formation strikes, according to Gabb, N. 25° W., and dips 10° NE. A little farther down stream the strike changes from N. 70° W. to N. 20° E., and the dip varies from 10° to 15° NW. On the Zhorkin, one mile below the mouth of the Izgui, the Gatun shale strikes due north-south and dips 15° to the west. A quarter mile farther down stream the strike is N. 30° W., and the dip 20° NE. On Shoai Creek, a short distance above its confluence

with the Zhorkin, sandstone of the Gatun formation strikes N. 18° W. and dips 30° NE.

The Pacific coastal range is, according to Pittier (31), the continuation of a fold which trends generally parallel to the main axis of the isthmus. The range consists of a number of parallel members, which suggests an *en échelon* arrangement of folds. A clearly defined anticline occurs in the gorge of Diquís River between Lagarto and El Palmar and is exposed at several points farther east.

Vulcanism.

Vulcanism appears to have been continuous in southern Central America from the Eocene or even the pre-Tertiary until the Recent. The Pliocene was, according to Olsson (28), a period of intense volcanic activity. The early Tertiary or pre-Tertiary periods of igneous activity are evidenced today by intrusions of plutonic rocks principally of acidic (?) or intermediate composition which form the cores of the Volcanic Range and the Sierra de Talamanca. The late Tertiary and post-Tertiary extrusives are generally of a basic composition.

The present volcanoes of southern Guatemala, Salvador, southern Honduras, and northern Nicaragua, occur in a few converging lines, which trend generally WNW.–ESE. A few are apparently arranged on short transverse lines normal to the usual trend. In Costa Rica and Panama, however, the majority of the volcanoes occur in a single arc on the crest of the North Costa Rican mountain range. Sapper (38) ascribed this difference in trend to the preëxistence of a mountain mass to the south, which prevented a displacement of the line of eruption. Certainly the lines of vulcanism in Costa Rica and Panama do not seem to have been displaced essentially since their greater activity in Tertiary times.

INDICATIONS OF OIL.

The best known oil seep in Costa Rica is located on Uscari Creek, one quarter mile above its junction with Amoura River, west of the town of Suretka. The oil reaches the surface along a fault plane cutting an outcrop of bluish-gray sandy shale, over

1,000 feet thick. The oil, which is dark green, with an apparent gravity of 28° Baumé (specific gravity 0.8861) issues at the rate of four to six quarts a day. The source of the oil is believed to be the Uscari formation (lower Miocene).

Scattered seeps yielding small amounts of oil have been noted at places along the Talamanca Valley. They are usually associated with or in close proximity to fault planes or shattered belts.

Near Urúchiko oil scum reported from a seep in a small ravine covers the head waters of Teleri (or Tarire) River, as the upper part of Sixaola River is known. Natural gas is reported to escape near Cahuita Point.

On the Pacific coast of Costa Rica, a few small seeps of oil and gas are said to occur in steeply dipping strata. These seeps have not been authenticated.

EXTENT OF POSSIBLE PETROLIFEROUS AREA.

The extent of the probable or even possible petroliferous area of Costa Rica is not easy to determine. As has been stated, geologic reconnaissances have been confined for the most part to three traverses across the isthmus. For a large part of the Tertiary sedimentary rocks of the Caribbean and Pacific slopes of the country, both stratigraphy and structure must be assumed.

In general it may be postulated that the favorable areas of both the Caribbean and Pacific coasts are relatively narrow in extent. In the zones which abut directly on the granite ranges which apparently underlie the late igneous flows of both parts of the central mountain system, one may postulate the close folding and steep dips which have been observed in fact in the Sixaola basin and along the Costa Rican Railroad. In this zone considerable faulting has occurred, and numerous intrusive rocks have been noted. On the contrary a zone of broader folding on the Caribbean slope has been noted by Hayes (19) in the Machuca formation of the central part of the San Juan valley. On the Costa Rican Railroad and in the Sixaola basin gentler dips are observed nearer the coast. Accordingly, the area to be considered favorably must be restricted to a relatively narrow zone midway between the mountains and the sea.

This zone has been prospected only in the basins of Sixaola and Estrella rivers. There the petroliferous character of the Tertiary sedimentary rocks is suggested by well authenticated oil seepages. Sharp unconformities exist, however, between the Tertiary formations, and detailed study of the local geology is required. The corresponding zone between the Costa Rican Railroad and San Juan River is largely covered by thick volcanic agglomerate which effectually masks the underlying stratigraphy and structure.

There is less certainty in postulating the existence of a petroliferous zone on the Pacific side of Costa Rica. Pittier (31), notes a folded structure in the Pacific Coast Range of southwestern Costa Rica. MacDonald (25), however, believes the prospects of finding oil in commercial quantities in the region from Golfo Dulce to Rio Barranca are not very good, owing to the proximity of volcanic rocks, the limited areas of the sedimentary rocks, and the alteration that the sedimentary rocks have undergone. More extensive zones of sedimentary rocks occur for several miles between Barranca River and Puntarenas, around the head of the Gulf of Nicoya, and on the southwest coast of Nicoya Peninsula.

CONDITIONS AFFECTING DEVELOPMENT.

Climate.

In general, Costa Rica has three climatic zones—torrid, temperate, and cold—which succeed each other with increasing altitude. Owing to the topography of Costa Rica, these zones extend generally north-and-south, parallel to the trend of the isthmus. The torrid zone, with a mean annual temperature varying from 72° F. to 82° F., comprises the low lying coastal plains and the foothills of the central ranges below 3,000 feet of altitude. It is broader on the Caribbean side of the isthmus than on the Pacific side. In the temperate zone of Costa Rica, which comprises the higher valleys lying generally between 3,000 and 5,000 feet of altitude, notably the Great Central Valley, the mean average temperature is 68° F., with an average variation

for all seasons of only 5° F. The cold zone includes the higher mountains.

The year is divided into a wet season (*verano*) and a dry season (*invierno*). The wet season, which lasts during the prevalence of the southwest monsoon, from April to December, is well defined on the Pacific slope. It is interrupted in June by a fortnight of dry weather known as the *Veranillo de San Juan.* On the Caribbean coast the wet season is less well defined; the northeast trade winds may bring rain in any month. The normal precipitation is about 80 inches a year; but as cloudbursts are frequent, it may exceed 150 inches.

Rheumatism on the Caribbean coast and malaria on both coasts are the commonest forms of disease. As a whole, however, Costa Rica is considered one of the healthiest of tropical countries.

Transportation.

There were in 1919 in central Costa Rica 700 kilometers (435 miles) of railroad of which 134 kilometers (83 miles) between San José and Puntarenas were Government-owned. The Costa Rican Railway Company and the Northern Railway Company of Costa Rica extend from Alajuela through San José and Cartago to Puerto Limón, with a branch from Siquirres to Guapiles, a branch from Puerto Limón to Zent, and a branch from Puerto Limón to La Estrella on Estrella River, or a total length of 566 kilometers (352 miles) in 1920. The entire mileage is operated by the Northern Railway Company, a subsidiary of the United Fruit Company, of New York. The United Fruit Company also operates a railway, 67 miles in length, with numerous spurs from Almirante, Panama, to Guabito, thence along the north bank of Rio Sixaola several miles beyond Sheroli and along the south bank to Sibube (Sibouwe).

The national highways maintained by the Federal Government constitute about 1,000 kilometers of roads connecting the towns of the Central Plateau with Puntarenas and with one another, and extend into the Department of Guanacaste. These roads have for the most part a good foundation, but are not well sur-

faced. Possibly 50 miles of these roads are fit for automobile use. The municipal and district roads are used exclusively for crude ox carts. They are usable in the dry season and mostly impassable in the wet season. Consequently the greater part of the country is without adequate means of communication in the dry season and practically shut off from the outside world during the long rainy season.

The streams of both the Caribbean and the Pacific slopes of Costa Rica descend by too steep a grade to the sea to afford navigation to any great extent; even the San Juan River has five series of rapids which can be traversed only when the river is in full flood.

LEGAL ASPECTS.

Ownership of minerals in the subsoil is vested in Costa Rica in the owners of the land. Private lands may be leased from the present owners by contract. Government lands may be prospected or explored by virtue of concessions in the form of contracts with the Costa Rican Department of State. Four important concessions covering Government lands have been granted: (1) The Pinto-Greulich concession of September 23, 1914, which gives exclusive rights for five years to prospect in the Provinces of Limón, Puntarenas, and Guanacaste, and exclusive rights to operate for 50 years the tracts "denounced" (claimed); (2) the Amory concession of May, 1918,[8] which gives for 50 years the right to explore and operate on public lands in the Provinces of Cartago, Alajuela, Heredia, and San José; (3) the Hereley concession of April 15, 1921, which confers for four years the right to prospect on public lands in the Provinces of Limón, Puntarenas, and Guanacaste; and (4) the Dolge concession, of June 4, 1921, which confers the right for 20 years to prospect on lands acquired from private owners, not to exceed 50,000 hectares (about 122,350 acres) in the Provinces of Limón, Guanacaste, and Puntarenas.

[8] Annulled by the Costa Rican Government, August 21, 1920. The diplomatic dispute over this annulment between Great Britain and Costa Rica is being arbitrated before Chief Justice W. H. Taft.

DEVELOPMENT.

In 1915 a well was drilled by the National Petroleum Company, holder of the Pinto-Greulich concession, with a portable churn-drill outfit in steeply dipping strata one mile west of the oil seep on Uscari Creek. No favorable indications were found, and the well was abandoned at 800 feet because of mechanical difficulties.

A well was located on Rio Blanco by the Costa Rica Oil Corporation (Sinclair), which had succeeded to the Pinto-Greulich concession, but was abandoned without drilling on April 5, 1918. Preliminary work was then begun on Uscari Creek, about seven miles from Suretka. This test is reported to have been unsuccessful.

A location for a new well was made on December 5, 1920, at Cahuita Point. The nature of the ground made drilling slow and expensive. Gas which was encountered at a depth of 825 feet caught fire on April 24, 1921, and destroyed the derrick and part of the equipment and tools. At the end of 1921 the well had reached a depth of 3,146 feet and had cost $303,273, including a loss of $25,000 due to the fire. By use of the diamond drill, the well was completed late in 1922 at a depth of 3,800 feet, without finding oil in commercial quantities. A new drilling site was located in March, 1923, about one mile inland from Old Harbor (Puerto Viejo) and preparations were made for drilling.

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U. S. GEOLOGICAL SURVEY,
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THE OCCURRENCE OF RUTILE IN THE TITANIFEROUS MAGNETITES OF WESTERN NORTH CAROLINA AND EASTERN TENNESSEE.[1]

W. S. BAYLEY.

INTRODUCTION

In the Appalachian and Piedmont districts of North Carolina are numerous bodies of titaniferous magnetites that have been known for many years. They have generally been regarded as consisting of ilmenite or of mixtures of ilmenite and magnetite, though Genth[2] as early as 1875 surmised that some of them might be mixtures of magnetic iron with titaniferous hematite, or menaccite, and probably also with rutile; but none of the constituents could be separated in a state of such purity that their true mineralogical character could be verified by analysis.

It has long been known that some of the ores richest in titanium exhibit no magnetism when subjected to the influence of an ordinary horseshoe magnetite. In these the titanium is probably present in ilmenite since if it were present in rutile, there would necessarily be present also considerable quantities of magnetite, and the mixture would be magnetic.

In 1913 Singewald[3] concluded as the result of his metallographic studies that some of the ores in the United States are pure

[1] Presented before the Society of Economic Geologists, Ann Arbor Meeting, December, 1922. The observations on which the discussion is based were made during a study of the iron-ores of the district under the auspices of the North Carolina Geologic and Economic Survey and the United States Geological Survey. Publication is with the permission of the Directors of these Surveys.

[2] Genth, F. A., Report of the Geological Survey of North Carolina, vol. 1, p. 244, 1875.

[3] Singewald, J. T., Jr., "The Titaniferous Iron Ores in the United States," U. S. Bureau of Mines Bull. 64, pp. 80–93, 1913.

ilmenite and others are intergrowths of magnetite and ilmenite.

However, an analysis[4] of the insoluble portion of a specimen of titaniferous ore from the Dannemora mine in Rockingham County, N. C., gave 11.82 per cent. TiO_2 and no iron. Evidently in this ore the titanium is in rutile or some other oxide. It cannot be in any compound of titanium except the oxide since only very small quantities of other constituents than SiO_2 and Al_2O_3 were shown by the analysis. (See p. 387.)

Thin sections of the ores from openings on the properties of Wm. Smith, and of C. Pennington, in Ashe Co., N. C., and from a pit in Lost Cove, Carter Co., Tenn., all show the presence of a yellowish-red rutile intergrown with an opaque ore-mineral which is probably in greater part magnetite.

Singewald[5] has called attention to the fact that Soligman, Cathrein and Mügge have described intergrowths of rutile and magnetite, and Warren[6] has pointed out that some of the analyses of titaniferous iron-ores from well-known localities show an excess of TiO_2 over that required for ilmenite. This he surmises is in the form of rutile, though positive evidence of the fact is lacking.

In the case described by Cathrein and Warren the rutile was in lamellar intergrowths in which the lamellæ were so narrow that it was difficult or impossible to identify the mineral with certainty.

On the other hand, intergrowths of rutile and ilmenite are shown by a few pebbles from placer concentrates on the Pacific Coast. In one there appeared to be a replacement of the rutile by the ilmenite, as the outside of the pebble was almost entirely ilmenite. Moreover, Mr. Hess has called the attention of the author to crystals from Shooting Creek, Clay County, N. C., that are intergrowths of a large proportion of rutile with a small proportion of ilmenite, and recently, Watson[7] has described and

[4] Tenth Census U. S., vol. 15, p. 311.

[5] *Op. cit.*, pp. 24, 27.

[6] Warren, C. H., "On the Microstructure of Certain Titanic Iron Ores," Econ. Geology, vol. 13, pp. 419–446, 1918.

[7] Watson, T. L., "Rutile-ilmenite Intergrowth," *Amer. Miner.*, vol. 7, p. 185, 1922.

given analyses of rutile crystals from a quartz vein in Franklin County, Va., that are intergrowths of ilmenite and rutile. The forms are those of rutile crystals, but their material consists partly of ilmenite, in one case described by the author, to the extent of about 40 per cent.

Further, in a rutile-sapphirine-ilmenite at St. Urbain, Quebec, Warren [8] finds the ilmenite to be thickly sprinkled with grains of an orange-red rutile, spinel and other minerals. The rutile is in the form of crystal grains or clusters, distributed nearly uniformly through a lamellar intergrowth of ilmenite and hematite. Again, in the rutile-nelsonite[9] of Goochland and Hanover Counties in Virginia the rutile may be intergrown with ilmenite, but the material is so thoroughly crushed that the nature of the intergrowth was not determined.

These observations indicate that whereas intergrowths of magnetite and rutile may be rare those of ilmenite and rutile are not uncommon.

MINERAL COMPOSITION OF THE ORES.

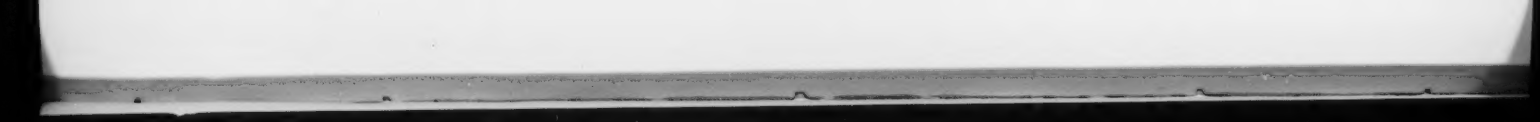
In the few sections of the North Carolina ores that have been examined microscopically rutile has been found in abundance. It is not in minute needles, nor in definite grains uniformly distributed through magnetite or ilmenite, but is for the most part in broad yellowish-brown translucent masses which in some cases are wider than the opaque magnetite or ilmenite between them. (Plate *XI*, A. C.) In the Tuscarora ore, however, it appears to exist in part as crystals imbedded in magnetite.

The appearance in the first variety is as though the rutile had formed along definite planes and had gradually replaced the magnetite or ilmenite on both sides,[10] until in some specimens

[8] Warren, C. H., "The Ilmenite Rocks near St. Urbain, Quebec; a New Occurrence of Rutile and Sapphirine," *Amer. Jour. Sci.*, 4th ser., vol. 33, pp. 263–277, 1912.

[9] Watson, T. L., and Taber, Stephen, "Geology of the Titanium and Apatite Deposits of Virginia," Virginia Geol. Survey Bull. III.–A.

[10] The appearance is very similar to that of the polished surface of the Tuscarora ore illustrated by Singewald (*op. cit.*, p. 88) in Pl. 7, *A*, where the light-colored bars are described as ilmenite.



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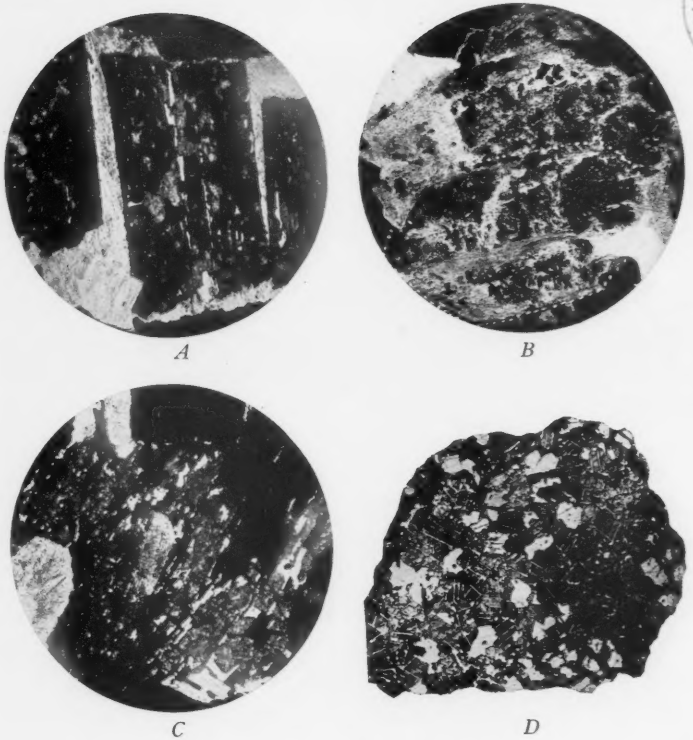

A

B

C

D

A. Titaniferous magnetite. Pennington Mine, Ashe Co., N. C. × 81. Black is magnetite or ilmenite; light gray, fibrous amphibole and chlorite. White streaks in the ore mineral are chlorite; dark gray, rutile, smaller masses of which do not show.

B. Same ore as *A*. × 60. Irregular aggregate of magnetite, amphibole, chlorite, and possibly serpentine, and areas whose outlines suggest olivine (white dots).

C. Titaniferous magnetite. Smith property, Ashe Co., N. C. × 100. Magnetite or ilmenite with irregular chlorite and serpentine (light gray) and rutile (dark gray).

D. Polished surface of ore. Tuscarora Mine, Guilford Co., N. C. × 2. Black is magnetite, and light gray is ilmenite. (Reproduction of fig. *C*, pl. II in Singewald's report on the titaniferous ores of the United States. Bur. of Mines Bull. 64. Courtesy of U. S. Bureau of Mines.)

there is now left only a narrow layer of the opaque mineral between neighboring layers of the brownish rutile. That the opaque mineral is magnetite rather than ilmenite is indicated by the strong magnetism of the ore. Of course, it is possible that the material of the ore grains was once an intergrowth of magnetite and ilmenite and that the present interlayering of magnetite and rutile is the result of some sort of metamorphism of the ilmenite.[11]

In the ore of the Tuscarora mine the rutile is apparently original, as some of its particles that are completely imbedded in the ore minerals show crystal outlines. Moreover, a few similar crystals are imbedded in the amphibole that lies between the ore grains. In the case of the Tuscarora ore it seems necessary to conclude that the rutile was one of the first minerals to form, as it was in the St. Urbain rocks and may be in the rutile-nelsonite of Virginia, being preceded only by spinel which occupies the centers of many of its grains.

Four thin sections of the Tuscarora ore, made from two specimens kindly furnished by Dr. Singewald, show the presence of many grains of red-brown, pleochroic rutile, a small quantity of a green transparent isotropic mineral that is probably pleonaste or a spinel closely allied to this, much opaque material and a very little colorless or very light green amphibole that may be anthophyllite. The opaque material is mainly magnetite with perhaps some ilmenite, but the two cannot be discriminated. The rutile occurs imbedded in the ore mineral and also to a less extent in the interstitial anthophyllite. Its particles bear the same relation to the opaque mineral as do the light and dark minerals shown in Singewald's photograph[12] of a polished specimen of ore (Plate *XI* D). The rutile in the ore occupies the positions corresponding to the light portions of the photograph. Most of it occurs in streaks about 1 millimeter long and about 0.12 millimeter wide, or in sharp-edged rhomboidal

[11] Compare Warren's comments on the intergrowths of ilmenite and hematite in the St. Urbain ilmenites: *Amer. Jour. Sci.*, 4th ser., vol. 33, pp. 266–7, 1912.

[12] *Op. cit.*, pl. II., *C*.

or wedge-shaped grains measuring about 0.7 by 0.3 millimeters in diameter, but it occurs also as very irregularly outlined pieces, as small crystals, as narrow rods and as little dust-like particles scattered irregularly through the magnetite. In the centers of some of its grains are little masses of a green spinel with very irregular shapes.

The Tuscarora ore is similar to the emery ore at Dobson Mountain in Macon County except in the proportion of the components present. It is true that no corundum was detected in thin sections of the Tuscarora ore, but the mineral is known to be present in the ore-mass.

The Dobson Mountain occurrence is on the northeast side of the divide between Cartoogajay and Skenah Creeks, about 4 miles west of Franklin. The ore is in a talcose amphibolite, which is thought by Pratt and Lewis[13] to occur as dikes near the borders of intrusive peridotite masses. The ore forms a series of indefinite veins " along a contact of a sort of talc or soapstone material."[14]

Thin sections of the ore show an aggregate of light green amphibole, colorless corundum splotched with blue, bright green spinel, reddish-brown rutile and opaque magnetite. The magnetite and rutile serve as the matrix by which the other minerals are surrounded. Magnetite and spinel are the most abundant components, followed by rutile, amphibole and corundum. The last named mineral, in the two slides studied, occurs in streaks through the aggregate and the rutile appears to crowd around the magnetite as though deposited upon it.[15] The ore is plainly a separation from the amphibolite phase of the peridotite magma.

CHEMICAL COMPOSITION OF THE ORES.

Gross Composition.—Two complete analyses and many partial analyses show the presence of chromium in all the samples of titaniferous ore in which it was sought, of an excess of Al_2O_3 in many and only a small quantity of manganese in any.

[13] Pratt, J. H., and Lewis, J. V., " Corundum and the Peridotites of Western North Carolina," North Carolina Geol. Survey, vol. 1, p. 251, 1905.

[14] From a letter of Mr. J. L. Stuckey.

[15] The Fixkörper-Absatz of Vogt. See *Jour. of Geol.*, vol. 29, p. 319, 1921.

ANALYSES OF TITANIFEROUS IRON-ORES FROM NORTH CAROLINA.

	I.	II.	III.
SiO_2	5.73	4.70	4.70
Al_2O_3	1.70	8.66	9.75
Fe_2O_3	45.51	43.05	.....
Cr_2O_3	.39	.34	.....
FeO	26.20	23.51	.....
MnO	.34	.15	.....
MgO	3.99	2.96	.72
CaO	Tr	1.42	.56
Na_2O	Tr	.05	.05
K_2O	Tr	.03	.03
BaO	.00	.....	.....
SrO	.00	.....	.....
TiO_2	12.96	13.71	11.82
P_2O_5	Tr	.052	.045
S	Tr	Pyrite .133	.....
CO_2	.00	.07	.....
V_2O_3	.00	.....	.....
F	.00	.....	.....
H_2O at 110°	2.81	.21	.....
H_2O above 110°	.06	.96	.....
.....	99.69	100.005	27.675

I. Sample of rich ore from Smith place, near Helton Creek, Ashe Co. Analyst J. G. Fairchild, U. S. Geol. Survey.

II. Whole ore from Dannemora mine, N. C. Tenth Census U. S., vol. 15, p. 311, 1886. There were also reported: NiS = .01, CoS = .03, CuS = .01, and C = .06.

III. Insoluble portion of II.

Titanium.—If it is assumed that all of the FeO in the Smith ore (I.) not required by the Fe_2O_3 to make magnetite, is present in ilmenite (and this is not the case for some of it is in soluble silicates), nevertheless, there is an excess of 6.7 per cent. TiO_2 present which probably represents rutile, and the ore consists of 66.2 per cent. magnetite, 12.1 per cent. ilmenite, 6.7 per cent. rutile and 15 per cent. silicates. The significant feature of the analyses of the Dannemora ore is the presence of 11.82 per cent. of TiO_2 in its insoluble portion and only 1.89 per cent. in its soluble portion. According to the analysis (II.) there cannot be more than 3.65 per cent. of ilmenite in the whole ore as against 11.82 per cent. of rutile. The ore is not a mixture of rutile and ilmenite but, rather, is a mixture of rutile and magnetite.

Analyses of samples of the ore from other openings show the

presence of TiO_2 varying between about 4 per cent. Ti to 96 per cent. Fe and 47.5 per cent. Ti to 52.5 per cent. Fe. In some samples which have not been examined microscopically, there is more than enough titanium present to form ilmenite with all the iron, consequently, it may fairly be assumed that in these, as well as in those that have been seen in thin sections, the excess of titanium is in rutile.

Chromium.—Moreover, in every sample in which it has been sought chromium has been found to be present in proportions varying between 0.34 per cent. and 1.19 per cent. of Cr_2O_3 in the whole ore, or from .007 to 2.3 parts Cr_2O_3 to 100 parts iron. It is evident that the chromium is associated with magnetite rather than with ilmenite, or rutile, since when an ore from the McCuiston place in the Tuscarora belt was subjected to the influence of a magnet, most of the chromium went with the magnetic portion.[16] Whereas about 95 per cent. of the TiO_2 went into the nonmagnetic portion nearly 77 per cent. of the Cr_2O_3 went with the magnetite.

COMPOSITION OF MAGNETIC AND NONMAGNETIC PORTIONS OF MCCUISTON TITANIFEROUS ORE.

	SiO_2.	Fe.	TiO_2.	Cr_2O_3.	Fe Calculated as Magnetite.	TiO_2 Calculated as Ilmenite.
Ore	12.75	41.95	15.35	1.25	43.12	29.15
Magnetic Portion	1.30	67.60	1.27	1.43	92.10	2.42
Non-magnetic Portion	26.80	21.63	16.20	.43	14.25	30.75

Nearly all titaniferous ores, wherever found, contain notable quantities of chromium. Watson[17] reports it in both the ilmenite and rutile of the Nelsonite district in Virginia and states[18] that Hasselberg found it in 10 of 12 rutiles examined by him. Kemp[19]

[16] Genth, F. A., Report of the Geological Survey of North Carolina, vol I., p. 245, 1875.

[17] *Op. cit.*, pp. 107, 119, 194, 1913.

[18] Watson, T. L., "Vanadium and Chromium in Rutile and the Possible Effect of Vanadium on Color," *Jour. Wash. Acad. Sci.*, vol. 2, p. 431, 1912.

[19] Kemp, J. F., "The Titaniferous Iron Ores of the Adirondacks," U. S. Geol. Survey, 19th Ann. Rept., pt. 3, p. 390, 1899.

declares that "at least traces of chromium are almost invariably present in titaniferous ores" and quotes[20] a number of analyses to substantiate his statement. The North Carolina titaniferous magnetites furnish another instance of this association, but in these ores the chromium appears to be in the magnetite rather than in the titaniferous component. It was not found in the rutile of the Dannemora ore. (Compare analysis III.).

On the other hand, titanium has not been reported in the chromite of North Carolina, nor is it known to be present generally in the chromite of other regions, though it has been found in the chromiferous iron ores of Mt. Poon, Greece, where an ore is mined containing 47.50–49.10 per cent. of iron, 2.19–2.45 per cent. of chromium, and 0.45–0.60 per cent. of titanium dioxide.[21]

Vanadium.—Vanadium also is declared to be a common component of titaniferous iron-ores. It is usually present in less than half of one per cent. of V_2O_5, but the titaniferous magnetites, Kemp states, are the only magnetites yielding more than traces of this oxide. Watson[22] reports it in the rutile and ilmenite separated from Virginia nelsonite and remarks that in the three specimens analysed the V_2O_3 is in excess of the Cr_2O_3. He reports[23] that Hasselberg[24] found vanadium in 12 rutiles and that in those rutiles studied by him in which vanadium was present in appreciable amounts chromium was also present, but in those in which vanadium was present in very small amounts chromium was absent or was present only in traces. In the North Carolina titaniferous ores, which are known to contain rutile, the chromium content is comparatively large and vanadium is absent. At least this is true of the two ores in which vanadium has been sought.

In view of Kemp's statement with reference to the association of vanadium and titanium it is interesting to note that the ore from

[20] *Op. cit.*, p. 387–388.

[21] Quoted from Cirkel's Report on the chrome iron ore deposits in the eastern townships, Prov. of Quebec., Dept. of Mines, Canada, Mines Branch No. 29, p. 9, 1909.

[22] Virginia Geol. Survey Bull. III.-*A*, pp. 107, 119, 194, 1913.

[23] *Op. cit.*, p. 228.

[24] Hasselberg, B., *Chem. News*, vol. 76, pp. 102–104, 1897.

the Smith place, in North Carolina, though it contains 12.96 per cent. of TiO_2 contains no V_2O_5 and there is none in the titaniferous ore of Lost Cove, Tenn. Moreover, none was reported by the chemists of the 10th Census in the ore of the Dannemora Mine, Guilford Co., N. C., though in this case the absence of this oxide from the record may be due to the fact that it was not looked for. On the other hand, the magnetite[25] of the Hibernia Mine in New Jersey, with only 0.54 per cent. of TiO_2 contains 0.14 per cent. of V_2O_3 (about 0.17 per cent. of V_2O_5), and that of the Richard Mine with only 0.30 per cent. of TiO_2 contains 0.11 per cent. of V_2O_3 (about 0.13 per cent. of V_2O_5).

Singewald[26] has already referred to the presence of vanadium in the New Jersey ores as controverting Pope's view [27] that the titaniferous magnetites are characterized by the presence of V_2O_5 in the ratio of about 1:28 of their TiO_2 content and that the nontitaniferous magnetities contain none. He shows that in the New Jersey ores the ratio of V_2O_5 to TiO_2 varies all the way between 1 to 3.2 and 1 to 11.9, instead of being always in the neighorhood of 1 to 28. If the New Jersey ores are not to be regarded as titaniferous, since they contain less than 1.5 per cent. of TiO_2, their analyses "indicate that a vanadium content is not characteristic of the titaniferous ores alone." The analyses of the Smith and Lost Cove ores, in North Carolina and Tennessee, indicate, on the other hand, that this oxide is not characteristic of all titaniferous ores. Moreover, analyses of the nontitaniferous ores of the Cranberry and Peg Leg mines show no V_2O_3. Thus we may fairly infer that presence or absence of vanadium in iron ores is more characteristic of the province in which the ores occur than of the variety of ore occurring in it.

Alumina.—The high alumina in many of the southern ores may be due in some to corundum and in others to a spinel. A green spinel has been noted in the ore of the Tuscarora Mine,

[25] Bayley, W. S., "Iron Mines and Mining in New Jersey," Geol. Survey of N. J. Final Report Series of the State Geologist, vol. 7, pp. 112–113, 1910.

[26] Singewald, J. T., Jr., *op. cit.*, p. 80.

[27] Pope, F. J., "Investigation of Magnetic Iron Ores from Eastern Ontario," *Trans. Am. Inst. Min. Eng.*, vol. 29, pp. 395–397, 1899.

and both spinel and corundum in the titaniferous emery of Dobson Mountain. Moreover, corundum is known to occur in many of the titaniferous ore-bodies at various points on the Piedmont Plateau in North Carolina. The analysis of the insoluble residue of the Dannemora ore indicates its presence in this ore.

OCCURRENCE AND ORIGIN OF THE ORES.[28]

All the titaniferous ores in North Carolina and Eastern Tennessee that have been studied occur as vein-like bodies associated with peridotites, olivine gabbros or talcose and serpentinous schists. In this respect they are very different from the non-titaniferous magnetites in the same district, which are always associated with pegmatite. At Senia P. O., which is at the mouth of Roaring Creek in Avery County, N C., the ore is in a series of small veins in websterite. At the Smith place, in Ashe County, the ore particles are in a weakly polarizing material in elliptical areas outlined by magnetite dust (Pl.*XI B*). This material under high powers is found to be composed of a light green, fibrous, chloritic mass containing minute spicules of a brightly doubly refracting mineral and particles of magnetite or tiny grains of rutile. If the streaks of magnetite dust that surround the elliptical areas mark the boundaries of some mineral that has disappeared, it is probable that this mineral was olivine, as the boundaries are like those of cross-sections of olivine. Other sections reveal a mass of fibrous minerals among which may be recognized actinolite, epidote and chlorite and a large quantity of a very finely fibrous material that is probably serpentine, forming a felt in which the other fibrous components and the ore grains are imbedded. In some places are curved lines of magnetite particles surrounding portions of the felt in a way that may mark the outlines of what were originally olivine crystals. The titaniferous ores of other deposits in Ashe Co. are of the same general character as at the Smith place. They consist of ore particles in a fibrous aggregate that may have been derived from olivinitic rocks. At the Tus-

[28] For a more detailed discussion of the origin of the titaniferous ores see: U. S. Geol. Survey Bull. 735-*G*, pp. 260–261, 1922.

carora Mine the rock immediately associated with the ore is an olivine gabbro.

Thus the titaniferous ores are associated with basic rocks, which elsewhere in the State are dunites, amphibolites and olivine gabbros,[29] containing corundum, spinel, chromite, and in some places rutile.[30] The ores always contain titanium, chromium and spinel and in some places corundum. At several places the mixture of magnetite, rutile, spinel and corundum, because of the large quantities of the last two named minerals present in them, are more properly ores of "emery" than of iron.

It appears probable, therefore, that most of the titaniferous magnetites studied are apophyses of dunite and peridotite magmas that have intruded pre-cambrian schists along their foliation planes in the form of narrow veins or flat lenses. In North Carolina, however, some of the ores are apparently free from gangue. These may have been deposited by hydrothermal processes, or they may represent late intrusions into cooled portions of the magma from which they were differentiated.

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[29] Pratt, J. H., and Lewis, J. V., North Carolina Geol. Survey, vol. 1, pp. 369–384, 1905.

[30] Pratt, J. H., and Lewis, J. V., *op. cit.*, pp. 277, 279, 280.

A PROTRACTOR FOR PLOTTING DIPS ON INCLINED SECTIONS.

H. E. McKINSTRY.[1]

In the geologic mapping of vein systems where vertical sections parallel to the strike of the veins are used to show structural features such as cross-fractures, faults, splits, and bedding-planes, apparent dips may be readily plotted by the aid of simple mathematical formulæ or by reference to dip-charts.

It is sometimes convenient, however, in the case of inclined veins having a regular dip and strike to represent mine workings and geology on sections which are not vertical, but which are taken parallel to the dip and strike of the vein. This seriously complicates the task of plotting features such as cross-fractures which intersect the plane of the vein. An attempt to work out a formula for the apparent dip in such cases was rewarded with

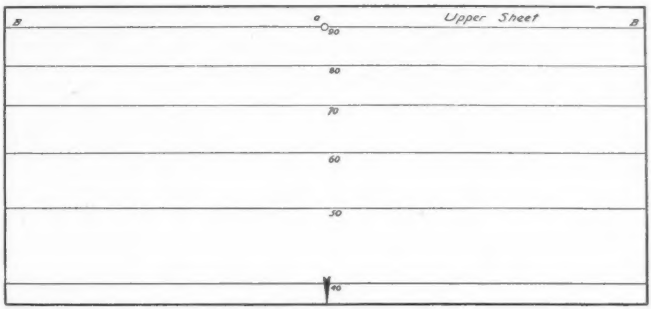

Fig. 61.

an imposing array of trigonometric functions too complicated for ready calculation. Even the graphic solution by descriptive geometry is somewhat laborious when a number of fractures with varying dips and strikes have to be plotted.

[1] Published with the permission of the Cerro de Pasco Copper Corporation.

To hasten the operation the writer has devised a form of protractor which has proved of great convenience. It consists of two sheets of transparent celluloid ruled as shown in Figs. 61 and 62 and fastened together by a small rivet at *a*. The ruling of the lower sheet depends upon the dip of the section on which the vein is represented, but the upper sheet has the same ruling regardless of the angle at which the section is inclined.

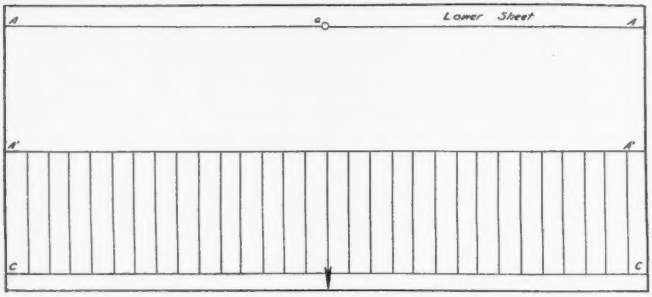

FIG. 62.

On the lower sheet the distance between the line *A–A* and the line *A'–A'* will be the natural cotangent of the angle of dip of the section, scaled with (say) 10 cm. as a unit. The distance from *A–A* to *C–C* will be the natural cosecant of the same angle plotted to the same scale. The closely spaced lines perpendicular to these are merely to aid in transferring points from one line to the other and may be any convenient distance apart.

The upper sheet bears parallel lines whose respective distances from the point *a* are the cotangents of the angles indicated by the numbers.

The sheets may be made of celluloid from an old automobile wind-shield or from heavy (portrait) photographic films washed clear with hot water. The upper sheet is placed upon the lower and the two are fastened together by means of an annular rivet such as is used in repairing steel tapes. The lines may be drawn with a needle-point and then inked.

In use, the protractor is placed upon a level-map or surface plan with the lower sheet (line *A–A*) held parallel to the line of the section (*i.e.*, the strike of the vein). The upper sheet is then turned horizontally with the rivet as a center until parallel with the strike of the fracture or bedding-place which it is intended to plot on the section, the arrow pointing in the direction of the dip. Then the protractor is picked up without changing the angle between the lines of the upper and lower sheets and laid upon the section with *A–A* parallel to any horizontal line (*e.g.*, a drift) and *a* upon a located point on the fracture. The point (*a'*, Figs. 63 and 64) of intersection of the line *A'–A'* with

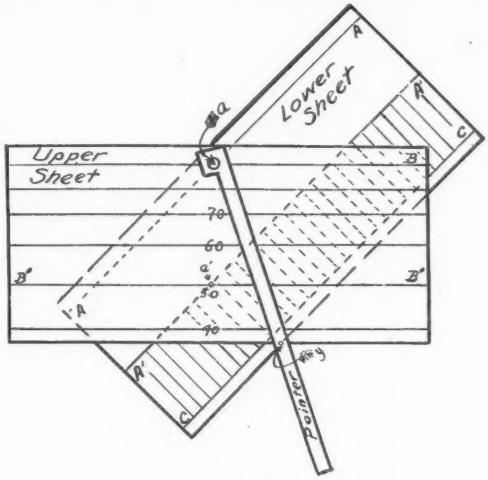

FIG. 63.

the line corresponding to the dip of the fracture (*e.g.*, *B'–B'* if the fracture happens to have a dip of 50°) is noted, and the corresponding point (*y*) on the line *C–C* marked. The line (*ay*) will be the line of intersection of the fracture with the plane of the inclined section and the angle *Aay* will be the apparent dip. The entire operation requires about one minute.

As an aid to plotting it is convenient to cut a pointer out of

celluloid and place it upon the top sheet, hinged at one end by the rivet *a*. It will serve as a ruler in drawing the line of apparent dip.

If gently inclined fractures or bedding-planes are to be plotted, the upper sheet will have to be made wider than shown in the illustration. If fractures which make a very small angle with the section are encountered, both sheets will have to be longer.

In theory, the operation of the protractor is of course analogous to the solution of the problem by descriptive geometry: Suppose that the longitudinal section is along an east-west line (*A–A*, Fig. 64) and dips 60° south. It is desired to plot on it a

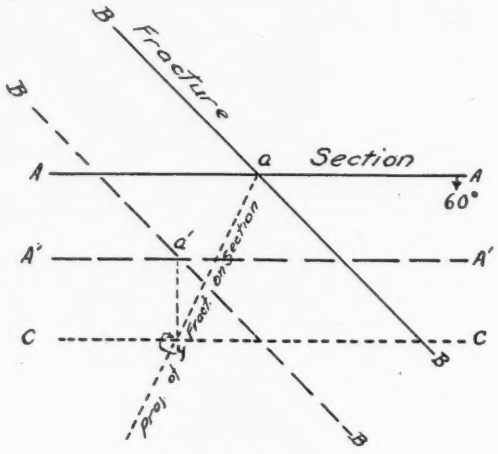

FIG. 64.

fracture (*B–B*) which strikes N. 45° W., and dips 50° SW. The obvious procedure is to plot the fracture on a horizontal plane (corresponding to a level-map or surface map); then imagine another plane passed horizontally a unit distance below this (*e.g.*, the level beneath) and draw the two lines in which the section and fracture, respectively, cut the lower horizontal plane. Their point of intersection (*a'*) is then plotted. Having two points (*a*

and a') common to the section and to the fracture, these will determine their line of intersection. Hence, turning to the section, if a and a' be plotted and connected it gives the line in which the fracture will intersect the section.

The protractor does this mechanically. It will be seen that *on the plan* the distance between the fracture at the elevation of a and its intersection with a plane a unit distance below is the cotangent of the dip of the fracture (in this case, cot. 50°). Similarly the distance between the line of the section and the line in which the section cuts a lower plane is the cotangent of the dip of the section (here cot. 60°). Thus, by plotting on one transparent sheet the traces of fractures of various dips, and on another the intersections on both planes of a section having a given dip, one can quickly find, by superimposing one sheet on the other at the proper angle, the point on the plan at which the traces of their intersection with the plane below will cross. If this point be carried perpendicularly down to the line C–C which represents the sectional view of the plane below, and the points a and y be connected, it gives a line representing the fracture on the section.

GEOLOGICAL OFFICE,
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A SUGGESTED EXPLANATION OF THE HIGH FERRIC OXIDE CONTENT OF LIMESTONE CONTACT ZONES.[1]

B. S. BUTLER.

INTRODUCTION.

THE material in this paper is taken mainly from a discussion of the ore deposits of the Cottonwood-American Fork district, Utah, a report under preparation by the U. S. Geological Survey.

After the presentation of the paper at the Ann Arbor meeting of the Society of Economic Geologists, Professor Adolph Knopf sent to the writer some unpublished notes on contact metamorphism which he had prepared several years ago. In these he called attention to the probability of oxidation of ferrous iron by carbon dioxide liberated from limestone, essentially as the writer has done. He made other observations, some of which the writer has included in this paper.

The writer is indebted to his colleague in the Cottonwood-American Fork work, Mr. F. C. Calkins, for his numerous suggestions and criticisms, and likewise to Dr. A. C. Spencer.

No attempt is made in these notes to review the voluminous literature on the contact metamorphism.

FERRIC OXIDE CONTENT OF LIMESTONE CONTACT ZONES.

It has long been a matter of record that many of the contact metamorphic zones in limestone are rich in iron. This has been especially true since Professors Kemp and Lindgren pointed out that the garnet of such zones is commonly andradite, the variety rich in iron.

That the ratio of ferric to ferrous oxide is comparatively high

[1] Published by permission of the Director of the U. S. Geological Survey. Presented at the Ann Arbor Meeting of the Society of Economic Geologists, December, 1922.

in many of the contact zones has not always or perhaps usually been emphasized though it is apparent from the abundance of ferric minerals as andradite, epidote, hematite, and magnetite.

Ferric oxide is present in larger proportion relative to ferrous oxide in the contact zone than it is in the intrusive rocks from which the mineralizing solutions are believed to have come on the one hand, or in the less intensely metamorphosed limestone at a greater distance from the contact on the other hand. That is, there is a zone adjacent to the intrusive body that is notably high in ferric oxide.

SOURCE AND CHARACTER OF MINERALIZING SOLUTIONS.

It has come to be pretty generally recognized that the solutions that produced contact metamorphism were derived from the same magmatic source as the rocks that form the intrusive bodies.

The character of the solutions is not so well understood. Ferrous oxide predominates over ferric oxide or is but slightly exceeded by the ferric oxide[2] in most intrusive rocks, both in those crystallizing in the early and in the later stages of magmatic differentiation, and it might be anticipated that the same relation would hold for the solutions given off by such bodies on crystallization.

In this study the assumptions have been made that the solutions on leaving the magma had a predominance of ferrous oxide, that the character of the iron oxide changed within the contact zone, and reasonable explanations of the supposed changes have been sought.

CONCENTRATION OF CARBON DIOXIDE IN THE CONTACT ZONE.

It is evident from the abundant silicates of calcium and magnesium in the limestone contact zones that the mineralizing solutions reacted vigorously with the carbonates and that large quantities of carbon dioxide must have been liberated. The presence of periclase[3] (MgO) in some contact zones suggests that there

[2] Clarke, F. W., and Washington, H. S., "The Average Chemical Composition of Igneous Rocks," *Nat. Acad. of Science*, vol. 8, No. 5, pp. 108–115, 1922.

[3] Rogers, A. F., *Am. Jour. Science*, 4th Ser., vol. 46, pp. 581–586, 1918. Calkins, F. C., U. S. G. S. Prof. Paper 111, p. 243, 1920.

may be a dissociation of the carbonates due to temperature alone. It seems certain that there must be a high concentration of carbon dioxide near the contact of a limestone and an intrusive rock immediately following the intrusion.

EFFECT OF HIGH CONCENTRATION OF CO_2 ON OXIDATION OF IRON.

Much has been learned about the chemical system carbon, oxygen, and iron because of its great importance in the production of metallic iron. This system has been discussed by Findley.[4] The stability relations of most interest in the present discussion of those of CO_2, CO, FeO and Fe_2O_3. Fig. 65 shows the stability relations for the equation $Fe_3O_4 + CO \rightleftarrows 3FeO + CO_2$.

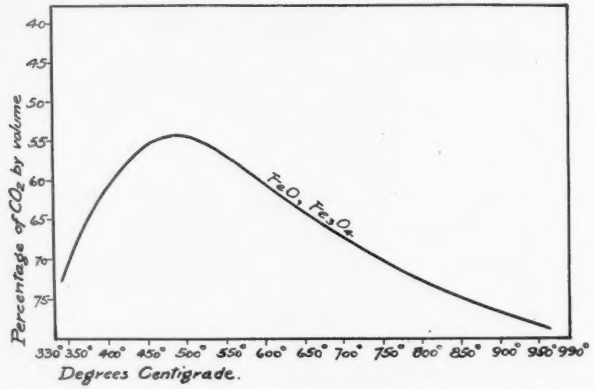

FIG. 65. Stability relations for the equation $Fe_3O_4 + CO \rightleftarrows 3FeO + CO_2$ after Findley.

The temperature most favorable for the movement of the reaction to the left is at 490°. Since the volume of gas is the same on both sides of the equation, this reaction is not affected by pressure and 490° is therefore the favorable temperature regardless of differences in pressure. If the concentration of CO_2 is sufficient, the FeO will all be oxidized to Fe_2O_3. With a suffi-

[4] Findley, Alex., "The Phase Rule and Its Applications," p. 313. Longmans, Green & Co.

ciently high concentration of CO and at a favorable temperature, the Fe_2O_3 will all be reduced to FeO.

It seems inevitable that a solution coming from a magma into limestone would pass through a zone high in carbon dioxide, and with favorable temperature the ferrous oxide of the solutions would in part be oxidized to ferric oxide and be deposited as ferric minerals. The portion that continued to move outward, however, would pass to a region of lower temperature and probably of higher concentration of CO, which had resulted from the reduction of CO_2 in oxidizing ferrous iron, and the reaction would then be reversed. In this region of lower temperature ferric oxide would be unstable and the iron would be deposited as ferrous silicates or carbonates. Any iron oxide that was an original constituent of the limestone would undergo similar change.

Dr. Knopf notes that in the contact metamorphism of a limestone only part of the CaO is combined as silicate and that much of it moves outward together with CO_2; as regions of lower temperature are reached, calcite gangue may be expected to form. Calkins (personal communication) has noted in the Cottonwood district that where dark cherty limestone shows incipient metamorphism the chert is partly replaced by white calcite. When, however, the conditions are such that the silica of the solutions no longer combines with the limestone to form silicates, CaO ceases to be added to the solutions, but the silica instead of forming silicates passes outward and it is likely that the earlier-formed calcite may be replaced by quartz. Knopf calls attention to the fact that such replacements are numerous and that no explanation has been advanced to account for the phenomenon.

TEMPERATURE OF FORMATION OF CONTACT DEPOSITS.

No very definite data as to the temperature of formation of the contact deposits are available. It appears to have been below the inversion temperature of quartz, 575°. In the Cottonwood district, Utah, dikes extending from the main intrusive had entered the limestone and solidified before the metamorphism was

completed. Both dikes and limestone were later affected by the solutions that produced the contact zones. Knopf observed similar relations in the Yerington district and they have been recorded from other districts. It seems, therefore, that the temperature may be approximately that most favorable to the oxidation of FeO by CO_2.

REDUCTION OF FERRIC OXIDES BY SULPHUR COMPOUNDS.

It has been shown that in a zone where temperature is favorable CO_2 may oxidize part of the ferrous iron of the magmatic emanations, but that further from the contact some of the iron may be again reduced by CO. Sulphur or sulphur compounds also may reduce ferric oxide as has been pointed out in another place,[5] and has been further emphasized in the papers on the genesis of native copper and allied deposits presented at the Ann Arbor meeting of this Society. The temperature most favorable for the movement of the reaction $2SO_2 + 3O_2 \rightleftarrows 2SO_3 + 2O_2$ to the right is about 400° or considerably below that most favorable for the oxidation of ferrous oxide by carbon dioxide. Data are not at hand to show the most favorable temperature for the reduction of ferric solutions by sulphur and sulphur compounds, but it is known that sulphur dioxide effectively reduces ferric solutions at a temperature of about 350° C and below.[6] The reducing effect of sulphur compounds if present would therefore be added to that of carbon monoxide as the solutions cooled in moving outward from the intrusive contact. The formation of SO_3 and its combination with the bases would result in the production of sulphates. Barite and anhydrite present in some of the lower temperature deposits are probably formed by this reaction.

[5] Butler, B. S., "Primary Sulphate Minerals in Ore Deposits," Econ. Geology, vol. 14, p. 581, 1919.

[6] Tobelman, H. A., and Potter, J. A., American Inst. Mng. Eng., Bull. 146, p. 475, 1919.

RELATION OF FERRIC OXIDE MINERALS TO SULPHIDES.

In the contact deposits at any given place, the ferric oxide minerals were formed for the most part in advance of the sulphides, and where sulphides were forming abundantly ferric oxide compounds did not form, and those that had formed previously were attacked. Both ferric oxide and sulphide minerals were probably forming at the same time during the early stages of mineralization but the sulphides were in general deposited farther from the contact and at lower temperature. There is, however, apparently a rather narrow range of conditions in which both ferric oxide minerals and sulphides are stable and we find them formed contemporaneously. The normal order appears to be ferric silicates and oxides, together with ferrous minerals, followed by sulphides with ferrous silicates and carbonates, and at lower temperatures sulphates. Relatively rarely there seems to be reversal of the order, and magnetite forms around sulphide grains or as veins in sulphide.[7] This reversal may well result from a temporary increase in temperature.

It has been the writer's experience in following veins into and away from a contact zone that as ferric oxide minerals become abundant, the sulphides, and especially the sulphides of lead, zinc and copper, rapidly decrease. There are valuable deposits in which the sulphides are accompanied by abundant ferric oxide minerals but in most of those observed by the writer, however, the sulphides have been deposited distinctly later than the ferric oxide minerals. Deposits in which the two types of minerals are contemporaneous were probably formed within a narrow critical range of temperature; they are therefore likely to pass abruptly into distinctly leaner or richer masses formed respectively at higher or lower temperatures.

Magmas are intruded at widely differing temperatures, and the character of mineralization varies accordingly. Magmas have been introduced at so low a temperature that scarcely any effect has been produced on the adjacent limestone. In some deposits ferrous oxide minerals predominate over, and were formed be-

[7] U. S. G. S. Prof. Paper No. 80, p. 84 and Plate 23, p. 184.

fore, the ferric oxide minerals. But, despite these variations, the majority of contact deposits seem to have had a history similar to that outlined above.

The reactions that result in contact deposits constitute essentially a chemical problem. Much is known of the system carbon, oxygen, and iron. If the physical chemist would add sulphur to the system and give us a discussion of the problem, it would be a decided contribution to the subject of ore deposits.

CALUMET, MICHIGAN.

EDITORIAL

THE EDUCATION OF THE GEOLOGIST.

To criticize the younger generation has ever been the favorite sport of those who are more advanced in years. At the outset I wish to disclaim any such intention, fully realizing that new conditions and new problems confront those that are entering upon their life's work. It can not be denied, however, that the tendency at the present time is strongly towards applied geology, and that the pure science is more or less neglected. There was a time (and it is still so in some European countries) when economic geology was considered something infra. dig. of geologists. Here, at least, this feeling has passed and the pendulum has begun to swing towards the other extreme. My experience has been mainly in a technical school, where the utilitarian view finds strong advocates but even in the larger universities the geological sciences as such appear to be neglected. The temptations are strong, it is true. Everywhere the young men see how substantial awards fall to the economic geologist and how little in comparison pure science has to offer. A suggestion of the worth of the scientific career of the teacher and investigator falls in the great majority of cases on deaf ears, or is dismissed with a smile. Practical life, action, money—these are the lights that seem to call the young men. So that even those who are deeply and genuinely interested in geology soon turn more or less definitely towards the applied science.

The recent great demand for petroleum geologists has resulted in vast numbers of young men following this branch, and too often they are turned out simply provided with the minimum of knowledge necessary for an "outcrop hound" or for the chasing of anticlinal structures, but quite useless for the advancement of geology.

I am certainly not belittling this tendency towards the practical. For many engineering professors a modicum of geology may suffice but, when the majority of geologists in a country concentrate on applications, pure science is sure to suffer.

No one can deny that we are approaching this dangerous stage in this country. Any one who has tried to obtain high grade teachers in mineralogy, petrography, or general geology will know how few and far between are the real first class men who have it in them to do pioneering work in their sciences.

We in this country have often enough been accused of hurrying, rushing, and trying to "get there" by the quickest road, and to some extent the change is well founded. The student who has passed through a four year course in geology and allied sciences think that he has little more to learn, and is first of all looking for rapid advancement, not realizing that only years of painstaking work and hard study lead to the top of the ladder. Particularly this applies to the economic geologist in the mining field. Too many regard applied geology simply as an engineering study which once mastered during a few years of study, will serve for a life time. Many of these men never publish anything, never try to advance the science or benefit their colleagues by writing their experiences. They are really petrified geologists, and of no use for the advancement of science. It is a healthy sign that high grade scientific societies begin to object to admit such men as members.

What is there to be done to remedy such an unfortunate state of affairs? Increased remuneration for teachers and investigators will do something, but nothing in the world will produce a great geologist but an intense devotion to this science coupled with talent or genius. I have little faith in research made to order, nor in elaborate equipment as a necessary requirement. The only really effective remedy is on the part of teachers to try to instil love of science in the minds of their ablest scholars. I believe that we should select the fittest and spend our time on them instead of trying to pound knowledge into the heads of those who in spite of intellectual inferiority try to make their way

through our courses. I confess to a hearty dislike for examinations, recitations, and quizzes, which are the approved means for accomplishing the object last stated.

I am not aware that there is any agreement as to the studies necessary for the education of the geologist. It will be found that the older men in geology have attained their position through many different paths of education. Some are purely self-taught. Others have passed through academic courses, and have been obliged to pick up their practical knowledge afterwards. Others have passed through engineering schools and there selected geology as their life work. Most of these men sooner or later find that they are deficient in some allied science, necessary for their work. Many find it necessary to study surveying, for instance. In former days little exact geological mapping was taught. Mapping was simply a case of hand compass, pacing, and a pre-existing topographic map. If the latter was wrong, so much the worse for the resulting geology.

Even now there is little uniformity in the requirements for a geological degree. Some universities will award such a degree with little reference to the fundamental sciences, deeming them only of secondary importance. I have known of cases in universities where a student has been allowed to take nearly every geological course offered, when he was totally innocent of any knowledge of analytical geometry, descriptive geometry, and trigonometry.

In the following lines I shall set forth what seems to be the necessary requirements for a first degree of B.S. in Geology. In the first place some knowledge in English, history, logic, and languages should be required. Those who first take their B.A. degree will, of course, be at a considerable advantage. One cultural language besides English should be required. For candidates for the Doctor's degree good reading knowledge of both French and German should be demanded.

Regarding mathematics, there is much diversion of opinion. It seems to me that calculus, including differential equations, is indispensable. Even if the student scarcely ever has an oppor-

tunity to use these subjects in research, he must be familiar with the processes by which so many of the problems of physics and chemistry are solved. The same applies to descriptive geometry, an instrument absolutely needful for the solutions of problems of structural geology. Many students I find are appallingly unfamiliar with these simple constructions. Physics and chemistry must be insisted upon, including some work in quantitative analysis.

Modern requirements include, at least, the principles of physical chemistry, with knowledge of the phase rule and ability to understand diagrams illustrating chemical equilibria. These latter subjects are becoming increasingly useful in the study of the relations of minerals. Courses in geology, paleontology, mineralogy, and petrography are, of course, essential. Strong emphasis should be placed upon the determination of minerals and on the conditions of mineral formation. Seminars in geology, comprising reading on various subjects are very effective in promoting interest and self-reliance. Stuffing and hand feeding should be discouraged and instead the student should be taught how to do the work himself. Practice in geological mapping needs not to be emphasized, but what must be insisted upon is a course in topographic surveying and familiarity with transit, level, and plane table.

Courses in economic geology, including ore deposits, nonmetallic deposits and hydrology are necessary. These courses should be accompanied by laboratory work in which the student is taught the construction of sections, and maps, and the examination and description of specimens of rocks and ores. The latter I have found by experience to be a most beneficial practice. The student may be able to determine the various minerals in sections and specimens, and yet be wholly unable to describe what he has seen. He dearly loves to launch into more or less hypothetical accounts of the origin of the specimen, but to make him describe in good English the actual relations observed is most difficult.

The courses in the various subjects should be carefully balanced

to avoid any specialization. That will come soon enough. His undergraduate years should be devoted to a preliminary study of all important phases of the science.

It is well, I believe, to allow a certain number of optional subjects according to individual tendencies in subjects of civil engineering, mining engineering, metallurgy, astronomy, meteorology and the like.

A course such as outlined above would fit the young geologist to take up a subordinate position in any branch of geology. If has the time and the means, post-graduate studies are most desirable. They are not essential for if he has been taught self-reliance in thinking and studying he will be able to acquire the advanced subjects by himself.

I know well that there is considerable difference of opinions among teachers in regard to some of these questions. It is hoped that others, who have longer experience and who are better qualified than myself may contribute to a discussion of the subjects here briefly referred to.

WALDEMAR LINDGREN.

DISCUSSION AND INFORMAL COMMUNICATIONS

THE FORMATION OF BAUXITE IN SINK-HOLES.

Sir:—In explaining the origin of bauxite deposits in Georgia and Alabama, C. W. Hayes[1] postulated the oxidation of iron sulphide to iron sulphate with the formation of sulphuric acid; the action of the sulphuric acid on the Connasauga shales which lie below the Knox dolomite; the movement of the aluminum sulphate thus formed toward the surface until reaction with a weak base, *e.g.*, calcium carbonate, produced gelatinous aluminum hydrate ; the transfer of this product to the surface by thermal springs occurring at or near faults and the deposition of it as bauxite in the basins of the hot springs or about them.

In this he followed Coquand and Augé[2] who ascribed the origin of certain bauxites in France to springs and geysers which brought the material to the surface and supplied it to lakes where it was deposited along with other sediments. While the theory advocated by Hayes may not be tenable, the descriptions of the deposits which he gave are detailed and satisfactory.

The explanation of the origin of the bauxites of Arkansas given by W. J. Meade[3] is simple. They are attributed to the weathering of syenite to kaolin and the desilication of the kaolin to bauxite by circulating surface waters. The action of percolating solutions on clays or kaolin at or near the fluctuating water-table, although not clearly understood, appears to account for the formation of most bauxite deposits. The writer believes that the Georgia-Alabama bauxite deposits originated in this way, and he

[1] U. S. Geol. Surv., 16th Ann. Rept., III.; 547, 1895.
[2] *Locus cit.*, p. 548.
[3] ECON. GEOL., vol. 10, 1915, pp. 28–54.

here offers the suggestion that the form of some of them is due to the accumulation and alteration of clays in sink-holes.

Recent field work in Alabama to the northwest of Piedmont, adjacent to the area described by Hayes, afforded an opportunity to examine some prospects and a worked out deposit of bauxite in Goshen valley. The form and surroundings of the deposit correspond to those of a typical sink-hole. There are many crater-like depressions in the vicinity in various stages of development and at varying altitudes. Some have one side broken down and others are rather indistinct. One occupies a position near the top of a hill and another is being filled with an accumulation of clay, washed from the surrounding hills which have been cultivated.

While it might not be unreasonable to conclude that bauxite is now forming in certain places in the region, especially where the bauxite grades into clays and the deposit is subject to the action of percolating water, it is proposed at this time simply to point out that certain deposits already formed and not modified by erosion, occupy crater-like depressions and that some pits found in the hillsides may be portions of deposits originally of similar form which have been partly removed. It is possible that as a result of erosion a deposit of bauxite, because of its resistance to weathering, might come to occupy the top of a hill even if formed in a sink-hole.

There may be many of the deposits which do not conform to the sink-hole theory as here set forth since although a sink-hole may function as a temporary lake, pond or depression and serve for the accumulation of clay that may become bauxite, a clay bed which shows no relation to restricted ponding may also be locally altered to bauxite. The point which it is desired to emphasize is that the bauxite deposits in crater-like depressions in Georgia and Alabama may be readily accounted for without appealing to the action of hot springs and geysers, and the transfer of material from great depth.

The sketch plan of the Warwhoop bauxite bank in Georgia by Hayes as well as his description of it tallies with that of a sink-hole. In it a bed of lignite was found associated with the bauxite.

Surely this was not a hot spring deposit. The lignite probably formed in a sink-hole when it functioned as a clear pond and the limonitic ore and ferruginous bauxite correspond to other stages of its history. Where ever the sink-hole mode of accumulation is applicable it will do away with the necessity of appealing to the action of hot springs and geysers and likewise permit of a simple explanation of the form and origin of the deposits. Further study may extend the number of occurrences which come under this type.

UNIVERSITY OF ALABAMA,
UNIVERSITY, ALABAMA.

GEORGE I. ADAMS.

ELECTRICAL PROSPECTING.

Sir:—I note with pleasure the review by R. C. Wells of my translation of Professor Schlumberger's "Study of Underground Electrical Prospecting" in the November issue of ECONOMIC GEOLOGY, vol. 17, 1922. As the science and art of Professor Schlumberger's method have both progressed considerably since the book was printed, I am taking the liberty of pointing out a few steps in the recent development which might conceivably be of interest to your readers.

In the first place I should like to call attention to the fact that the process described in Chapter 9, namely that of spontaneous polarization, has in the last three years proved to be the most valuable in the prospecting for metallic sulphides. The fear that a virgin deposit of pyrite would give but slight electrical indications as compared to those given by a deposit under exploitation, due to the more lively oxidation of the latter, has proved to be groundless. Professor Schlumberger verified this when returning to the mines of Sain-Bel to check results obtained a number of years before. At his first visit he had indicated the location of a hitherto undiscovered lens of pyrite. At the time of his second visit this lens had already been opened up for a number of years, but the potential differences observed at the surface were unchanged (see page 95 of the text reviewed).

Moreover, Professor Schumberger has already modified his original theories regarding the generation of the underground current. Originally he ascribed this current to the chemical action of oxidation of the pyritic substances. In a communication to the Academy of Sciences (*Comptes Rendus,* vol. 170, 1920, p. 519) he says: "Any mineral mass which possesses metallic electrical conductivity throughout a sufficient depth, and which lies underground in such a fashion that part of it rises above the water table, produces in the surrounding moist terrain electrical currents observable by the differences of potential which they produce." This electrical action is probably due to the activity of the dissimilar waters of the oxidation and cementation zones when in contact with the metallic mass.

For the last sixteen months I have been in this country representing Professor Schlumberger, conducting experiments at various mining camps of the United States and Canada. The results of these experiments I have outlined in two articles published by the "Engineering and Mining Journal Press" in the issues of October 7 and 14.

These experiments indicate the applicability of the process to certain anthracite coal veins, nickel deposits of the Sudbury type, gold deposits of the Hollinger type and silver cobalt veins such as those found near Cobalt. At the same time they show the failure of the method at Kirkland Lake and Calumet. At the latter mines Professor Schlumberger's first method, described at length in his book, gave some promise of success.

More recently I have made some experiments on disseminated copper deposits, the results of which I hope to make public soon.

SHERWIN F. KELLY.

LAWRENCE, KANSAS.

REVIEWS

Cannel Coals, Lignite and Mineral Oil in Scotland. By W. GIBSON.

This paper, which contains contributions by Director J. S. Fleet, E. M. Anderson, G. W. Lee, and M. Macgregor, as well as Doctor Gibson's portion, embraces descriptions, with columnar sections, of the cannel coal and canneloid deposits of the Coal Measure and Mississippian formations of Scotland, with estimates as to the areas of the beds, measurements of thickness, and some determinations of oil yield by distillation.

The report, a short one, is of some value to coal and oil shale geologists for its analyses and a few retort tests. The conclusions reached are to the effect that the cannel deposits are too limited to serve as a basis for oil production, while the unworked oil shales are in general too lean. In short, the richest oil shale deposits, including the bogheads of Scotland, now appear to be largely worked out. The oil shales of the Jurassic and the Tertiary lignites are very restricted and appear to be of little value, either for fuel or oil production, though a little of the Tertiary coal is still being mined. The paper, a memoir of the Geological Survey of Scotland, appears to constitute a clean-up of war geological work on the raw materials in Scotland that might be used for oil and wax production.

DAVID WHITE.

Cements and Artificial Stone. By JOHN WATSON. Edited by R. H. RASTALL. Cloth, 131 pages, 4¾x7¼. W. Heffer & Sons Lt., Cambridge (England), 1922. Price, 6s.

This little book is a description of the collection of specimens illustrating cements and concrete materials in The Sedgwick Museum. Although dealing only with materials employed by manufacturers in the British Isles the book contains many hints on the use of other than the ordinary materials in the making of cements, and the effect of the substitutes on the properties of the finished products. Methods of preparation of the raw materials are described briefly and the peculiar characteristics of the different kinds of cements are outlined.

The cements discussed are: Portland, Fibrent, Stucco, Hydraulic Lime, Selenitic, Roman, Plaster of Paris, Keen's, and Sirapite.

Not the least interesting features of the volume are the numerous historical references scattered through the text.

W. S. B.

SOCIETY OF ECONOMIC GEOLOGISTS

This department has been established for the official communications of the Society of Economic Geologists whereby the affairs of the Society such as notices, minutes, titles of papers, elections, etc., may be brought regularly to the attention of its members.

By the ballot that closed May 1st, the following new members were elected:

Joseph A. Bancroft	F. Julius Fohs	Percy Wagner
Arthur C. Bonine	Donald H. McLaughlin	Alfred Wandke
Charles W. Cook	J. H. L. Vogt	C. M. Weld
	Herbert A. Wheeler	

The above elections were confirmed at the Council and Executive Committee meeting held May 4th.

The Society held its Technical Meetings on May 18th and 19th in the United Engineering Building, 29 W. 39th Street, New York. Four sessions were held, attended by 44 members and 26 guests. The papers presented were excellent. They were followed with attention and were discussed at length enthusiastically. The list of papers presented was given in the previous issue of ECONOMIC GEOLOGY and later a majority of the papers will be published in these pages.

Friday night a smoker was held at the Columbia University Club, at which old friendships were renewed and new ones made. Approximately 35 members attended.

On Saturday night a dinner was given at the Harvard Club, attended by some 40 members and guests. Professor J. F. Kemp was Toastmaster, and President Spurr, President Mathewson of the American Institute of Mining and Metallurgical Engineers, President David White of the Geological Society of America, W. C. Mendenhall, Chief Geologist, U. S. Geological Survey, Professor N. F. Fenneman, Chairman, Division of Geology and Geography of the National Research Council, Professor Alan M. Bateman, Editor of ECONOMIC GEOLOGY, Acting Director P. S. Smith of the U. S. Geological Survey, and Dr. George H. Ashley, State Geologist of Pennsylvania, spoke. At the dinner the Society medal, presented to the Society by R. A. F. Penrose, Jr., was for the first time exhibited.

SCIENTIFIC NOTES AND NEWS

Morris M. Leighton has been appointed Chief of the Illinois State Geological Survey to succeed Frank W. DeWolf, who resigned on March 20th. Dr. Leighton, who is at present Associate Professor of Geology at the University of Illinois, has for several years maintained a part time connection with the Illinois State Survey. He graduated from the University of Iowa, received his doctor's degree from the University of Chicago, and has since been engaged in the teaching of Geology at the University of Washington, at Ohio State University, and at the University of Illinois. Dr. Leighton will assume his new duties in June, at the conclusion of the present school year.

H. Schneiderhöhn, Professor of Geology, at the University of Giessen, recently visited Scandinavia, lecturing on the microscopic examination of opaque minerals at the University of Christiania and the School of Mines in Stockholm.

Kirk Bryan, of the U. S. Geological Survey, is carrying on the field work for the investigation of the Columbia Basin project.

A. W. Ambrose has resigned as assistant director of the U. S. Bureau of Mines to enter the service of the Empire Oil & Gas Co.

Arthur L. Day, director of the Geophysical Laboratory of the Carnegie Institution at Washington, was presented with the John Scott medal and an accompanying premium of $1,000 at a meeting of the American Philosophical Society, in recognition of his work in the interpretation of geological phenomena and the production of optical glass.

Sidney Paige has been transferred to the Alaska branch of the U. S. Geological Survey as geologist in charge of three parties that will make a survey this summer of Naval Petroleum Reserve No. 4, on the Arctic coast of Alaska.

G. W. Stose of the U. S. Geological Survey has returned to Pennsylvania for field work.

J. B. Tyrrell of Toronto is in charge of operations at the Porcupine Keora Mine.

E. F. Burchard is on a field trip in connection with the mineral resources and geological work of the U. S. Geological Survey.

G. C. Bateman, general manager of the La Rose Mines, Ltd., was reelected a director of the company.

John W. Finch has returned to New York after a trip through Europe, the Near East, and Egypt.

G. R. Mansfield, of the U. S. Geological Survey, has been in Tallahassee, Florida, examining phosphate lands in coöperation with the General Land Office.

Vincent C. Peet is in the department of petroleum and gas of the California State Mining Bureau.

E. E. Jones, of the U. S. Geological Survey, has started six months' field work in Montana, Wyoming, and Colorado.

P. H. Reagan is with the geological department of the Copper Queen Mining Company at Bisbee, Arizona.

T. M. Prettyman, formerly of the Geological Survey of Georgia, is now geologist with The Texas Company, at Houston, Texas.

M. Legrayl and Eugene Poncelet, Belgian mining engineer, have been in Arizona visiting the large copper mining and smelting districts.

F. F. Sharpless, Secretary of the American Institute of Mining and Metallurgical Engineers, visited Toronto recently to make arrangements for the excursion of the Institute to the mining districts of northern Ontario.

S. M. Soupcoff has been made consulting engineer for the western division of the American Smelting and Refining Company, with headquarters at Salt Lake City.

Ralph T. Hirsh, mining engineer for the N. Y. Alaska Gold Dredging Company, has returned to New York from Alaska, where he visited the lower Kuskokwim district.

N. O. Lawton is engaged in professional work at Eureka, Nevada.

R. B. Moore, chief chemist of the Bureau of Mines, discussed hafnium and other rare and suspected elements before the New York section of the American Chemical Society on June 8.

C. Mason Farnham has returned to Barre, Mass., after a two years' study of the diamond mines of Angola and the Belgian Congo, the copper mines of the Katanga, and the producing mines of South Africa.

Yale University has received securities valued at $25,475 from Mrs. Estelle Iddings Cleveland, being the entire estate of her brother, the late Professor Joseph Paxson Iddings, for the establishment of the "Iddings Fund" for the promotion of research in petrology.

The State of Colorado, in coöperation with the Bureau of Mines, has published Bulletin 210 on Oil Shales, by Martin J. Gavin. It describes the occurrence of oil shales, their oil content, and the problems to be solved in their treatment. Copies may be obtained from the U. S. Bureau of Mines, Boulder, Colorado.

The Washington Academy of Sciences held a meeting jointly with the Geological Society of Washington and the Philosophical Society of Washington, on April 18, to discuss the Taylor-Wegener hypothesis. The papers were: Frank B. Taylor, The Lateral Migration of Land Masses; R. A. Daly, A Critical Review of the Hypothesis; W. D. Lambert, The Mechanics of the Hypothesis; Fred E. Wright, Report of the Symposium at the Meeting of the British Association.

The Carnegie Institute of Technology will employ six college graduates next year for coal-mine research and investigations in the utilization of fuels, under the supervision of the U. S. Bureau of Mines. Six Fellowships of $750 each are offered to graduates of universities and technical schools.

George K. Burgess has been appointed director of the Bureau of Standards. He was formerly chief of the Bureau's Division of Metallurgy.

S. J. Schofield, of the University of British Columbia, has been granted leave of absence for a year to carry on a geological survey in China. He will leave shortly for Hongkong.

Alfred W. Stickney expects to be in New York for some little time.

Esper S. Larsen, of the U. S. Geological Survey, has been appointed professor of petrology at Harvard University.

F. W. Stillwell, mining geologist of Melbourne, Australia, has been visiting several American mining camps before his return to Australia, including Leadville and Cripple Creek, Colorado, Jerome, and Globe, Arizona, Virginia City, Nevada, and the Mother Lode and Grass Valley districts of California.

Sidney A. Packard has left the Colorado School of Mines for Portuguese West Africa, where he will be engaged in petroleum exploration for the Sinclair Oil Company.

J. K. Walsh, professor of mining and geology at the Oklahoma School of Mines, has been elected president of that institution.

McHenry Mosier has been appointed assistant mine superintendent at the Morenci Branch, Phelps Dodge Corporation.

Leopold Reinecke, formerly on the staff of the Geological Survey of Canada, and recently with the Sinclair Oil Corporation in Angola, is commencing practice as a consulting geologist in Johannesburg, Transvaal.

Kirtley F. Mather has been appointed professor of geology at Harvard University for one year.